Evaluating Source Geometry Dependencies in ^{177}Lu Measurements with Air Communicating Well-Type Ionization Chambers

Likhitha Polepalli[1], Peyton Lalain[1], Sean Jollota[1], Denis Bergeron[2], Larry DeWerd[1]

[1]Department of Medical Physics, University of Wisconsin-Madison, Madison, WI, 53705
[2]Radiation Physics Division, National Institute of Standards and Technology, Gaithersburg, MD, 20899

Purpose: Radiopharmaceutical therapy (RPT) utilizes unsealed radionuclides, such as ^{177}Lu, for targeted radiation cancer treatments. Precise quantification of administrated activity, traditionally measured using radionuclide calibrators, is the critical first step in patient-specific dose estimates [1]. However, these radionuclide calibrators are sensitive to source geometry variations (container material, solution volume), causing inaccuracies up to 20% in clinical settings [2]. Alternatively, air-communicating well-type ionization chambers, typically employed for brachytherapy, could be utilized. The purpose of this study was to determine geometry-specific calibration coefficients (pA/MBq) for an air-communicating well chamber and electrometer setup. Establishing these coefficients allows for the direct and precise conversion of chamber current readings into activity measurements for various source geometries.

Methods:
Four vial geometries (2mL V-vial with 2mL of 0.005mol/L HCl, 10R vials with 5mL of 0.005, 0.05, and 1.0mol/L HCl) and three syringe geometries (1, 2, and 3mL of ^{177}Lu in 0.05 and 1.0mol/L HCl) were evaluated. A Capintec CRC-55tR pressurized radionuclide calibrator was calibrated with a National Institute of Standards and Technology (NIST) massic activity reference to establish traceable activity measurements for 10R vials. To calibrate the chamber, readings were acquired across dial settings systematically varying in 1 unit increments up to twenty dial settings above and below the manufacturer value of 450 * 10. V-vials, while not NIST-traceable, were included to assess measurement differences stemming from vial thickness.

Current measurements were obtained using air-communicating Standard Imaging (SI) HDR 1000+ and IVB 1000 well chambers connected to SI MAX 4000 or MAX 4000 Plus electrometers (+300 V bias). Custom 3D-printed holders ensured reproducible positioning at the sweet spot. A custom Python script automatically recorded charge readings every 60 seconds over a 10 minute duration. To quantify transferred activity and micropipette solution loss, ^{177}Lu solutions were transferred between vials; mass and activity of the full and empty vials were measured to calculate transfer residual loss.

Results:
The Capintec CRC-55tR calibration curves with low fit uncertainties (<0.13%) were compared against the NIST provided activity that yielded specific dial settings (10R: 450, 1mL syringe: 464, 2mL syringe: 469, and 3mL syringe: 470). Radionuclide transfer studies quantified minimal residual mass and activity losses during solution transfers: 7.68±1.41 mg (0.45±0.09% activity loss) for 0.05mol/L HCl, and 12.36±6.80 mg (0.63±0.29% activity loss) for 1.0mol/L HCl.

Initial chamber evaluations revealed that thicker V-vials yielded lower currents than 10R geometries (Figure 1). The prototype SI HDR 1000+ equipped with a C552 wall exhibited continuous signal drift. While the standard SI HDR 1000+ was stable, its dimensions could not accommodate syringe geometries. Therefore, the SI IVB 1000, which produced high signal amplitudes and accepted syringes, was selected as the optimal non-pressurized detector. Changing solvent molarity (0.05 vs. 1.0mol/L) yielded negligible change in detector response (0.14% in Capintec, 0.04% in SI IVB). Despite variations in absolute activity between source shipments, mean activity-normalized responses remained highly consistent across multiple independent 10R vials over several months, averaging 0.885(13) pA/MBq for the Capintec and 0.0165(6) pA/MBq for the SI IVB 1000.

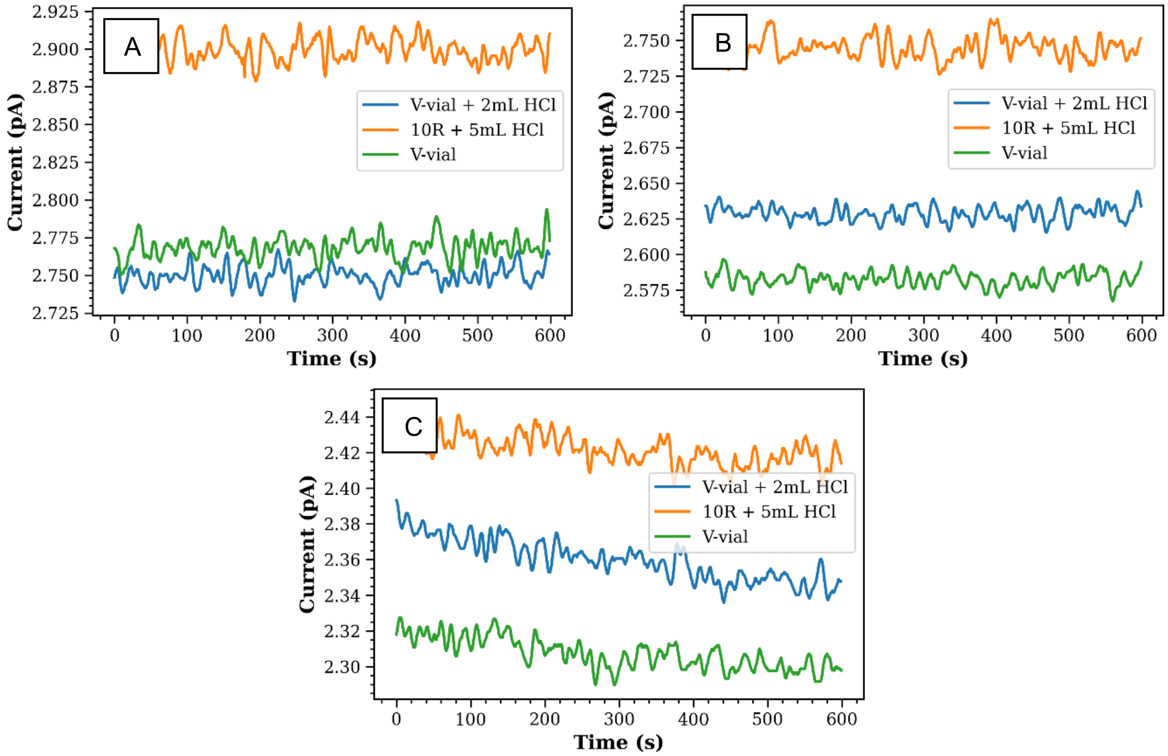

Figure 1: Current (pA) measurements comparing V-vial and 10R geometries across (A) SI IVB 1000, (B) SI HDR 1000+, and (C) SI HDR 1000+ (C552 wall)

To evaluate varying source volumes, a sequential syringe dilution protocol was executed: a 1mL ^{177}Lu aliquot was measured, then sequentially diluted with HCl to 2mL and 3mL. This isolated pure geometric effects without confounding the data with increasing absolute radioactivity. Normalizing integrated charge to absolute activity (pC/MBq) revealed the geometric dependencies (Figure 2). The Capintec 12-atm exhibited a slight upward trend, increasing from 54.53±0.04 pC/MBq at 1mL to 54.94±0.03 pC/MBq at 3mL. Conversely, the non-pressurized SI IVB 1000 demonstrated volumetric stability, remaining virtually flat between 1.006±0.004 pC/MBq and 1.008±0.004 pC/MBq, effectively neutralizing the geometric differences observed in the calibrator.

Synthesizing this empirical data with a comprehensive uncertainty budget (Table 1), highly precise calibration coefficients (pA/MBq) were derived for all tested geometries (Table 2). By explicitly calibrating the Capintec CRC-55tR, the generic manufacturer-stated dial setting and syringe geometry uncertainties (4.04% and 1.15%, respectively) were excluded, yielding a much lower combined uncertainty.

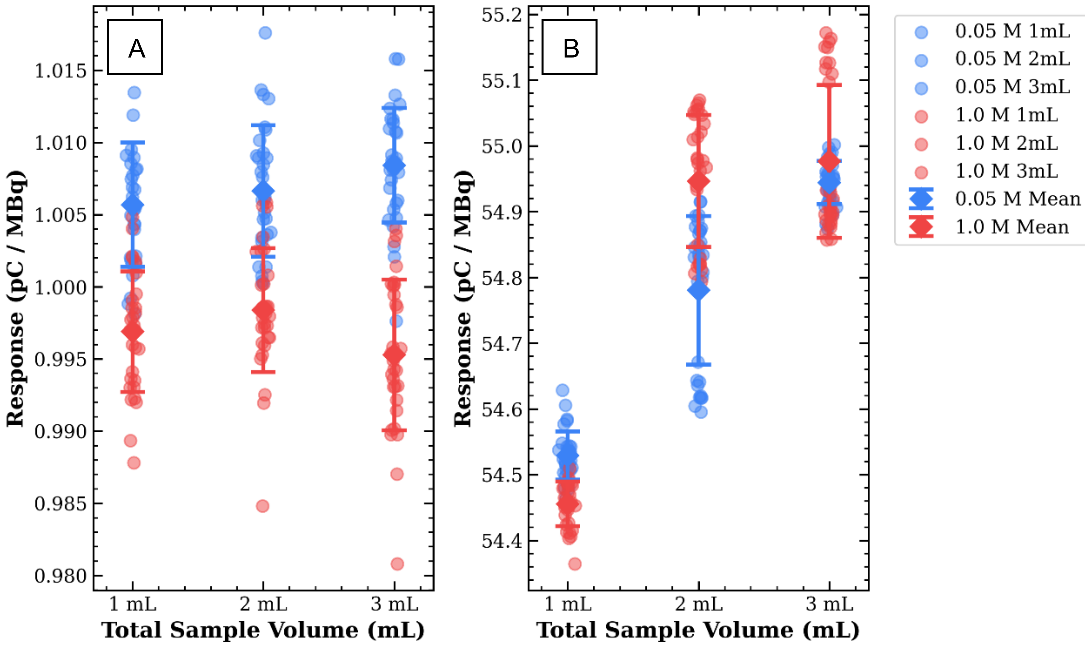

Figure 2: Activity-normalized charge (pC/MBq) isolating volumetric geometric dependencies in the (A) SI IVB 1000 and (B) Capintec 12-atm

Table 1: Uncertainity Budget for SI IVB 1000 and 10R vial with 0.05 mol/L HCl

Quantity	Type A (%)	Type B (%)	Comment
Repeatability (charge)	1.8		Standard deviation from measured data
NIST		0.66	Uncertainty from NIST provided massic activity
Fit		0.067	Propagated from the Capintec calibration curve used to determine sample activity
Half-Life		0.00020	Estimated by propagating the half-life uncertainty (6.6443 ± 0.0009 days from LNHB) with the largest decay correction [3]
Pressure and Temperature		0.040	Triangular distribution of ±0.1°C and ±0.1 kPa variability range
Electrometer Resolution		0.029	Rectangular distribution based on resolution of electrometer (±0.0005 pA)
P_{elec}		0.050	ADCL uncertainty k=1
Mass		0.010	Sartorius Quintix 65-1S Uncertainty from Manufacturer [4]
Combined Uncertainty	1.8	0.67	Combined in quadrature
Standard Uncertainty	1.9		Combined type A and B uncertainties
Expanded Uncertainty	3.9		k = 2 uncertainty confidence interval

Table 2: Calibration Coefficients for 10R and Syringe geometry

Geometry	Molarity (mol/L)	SI HDR 1000+ (pA/MBq)	SI IVB 1000 (pA/MBq)	Capintec 12 atm (pA/MBq)
10R	0.05	0.0150(5)	0.0165(6)	0.885(13)
10R	1	—	0.0170(3)	0.885(12)
Syringe 1mL	0.05	—	0.0150(12)	0.908(25)
Syringe 2mL	0.05	—	0.0160(14)	0.924(25)

Conclusions: This study determined geometry-specific calibration coefficients for ^{177}Lu using air-communicating (SI IVB 1000 and SI HDR 1000+) and pressurized (Capintec 12-atm) well-type ionization chambers. Solvent molarity (0.05mol/L versus 1.0mol/L HCl) had a negligible impact on detector response. Furthermore, volumetric expansion inside syringe geometries revealed stability in the SI IVB 1000, while the Capintec 12-atm exhibited a slight geometry dependence. Ultimately, the SI IVB 1000 proved to be a highly robust alternative to standard radionuclide calibrators.

Relevance to CIRMS: This research directly aligns with the CIRMS mission to advance physical standards and quality of radiation dosimetry. By establishing precise, NIST-traceable calibration coefficients for ^{177}Lu sources, this work addresses existing metrological challenges in RPT and minimizes geometrical uncertainties common in standard clinical radionuclide calibrators. CIRMS aids my professional goals by allowing me to engage with radiation metrology experts and create collaborations for a future career in medical physics.

References:

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