Nondestructive Volume Determination of Commercial Ionization Chamber using Various micro-CTs

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Purpose: Absolute measurements offer the highest metrological quality. Ionization chambers with precisely determined sensitive volumes are used for primary, absolute measurements of air-kerma for photons with maximum energies above 300 keV. However, accurate volume determination for air-kerma standards is non-trivial and requires precision exceeding manufacturer tolerances and calibration coefficient-derived calculations. Traditionally, known-volume chambers have been limited to primary standards laboratories, where the geometric volume is determined through chamber disassembly methodologies such as gravimetry or mechanical measurements (i.e. coordinate measuring machines). The geometric volume then yields the sensitive volume after corrections are applied for electric field inhomogeneities. Micro-CT is widely accessible in many research institutions and offers a non-destructive alternative to characterize the geometric volume of ionization chambers. In this work three different micro-CT systems, (i.e. MII Labs SPECT/CT, Mediso PET/CT, and Neoscan N80 Industrial micro-CT) were compared. This allowed the determination of the geometric volume of an Exradin® A3 commercial ionization chamber.

Methods: The collecting volume of an Exradin® A3 ionization chamber was determined using three micro-CT systems with differing imaging capabilities: the MII Labs SPECT/CT, Mediso PET/CT, and Nesoscan N80 with respective voxel sizes of 20 μm, 25 μm, and 35 μm. Acquisition parameters were optimized for image quality, artifact minimization, and inter-scanner comparisons. From the micro-CT scans, binary segmentation thresholds for each scanner were determined using the ISO-50 method to distinguish the inner air cavity from C552 wall and collector material. Thresholds were calculated by averaging air and C552 intensity peaks from line profiles across axial slices (Figure 1).

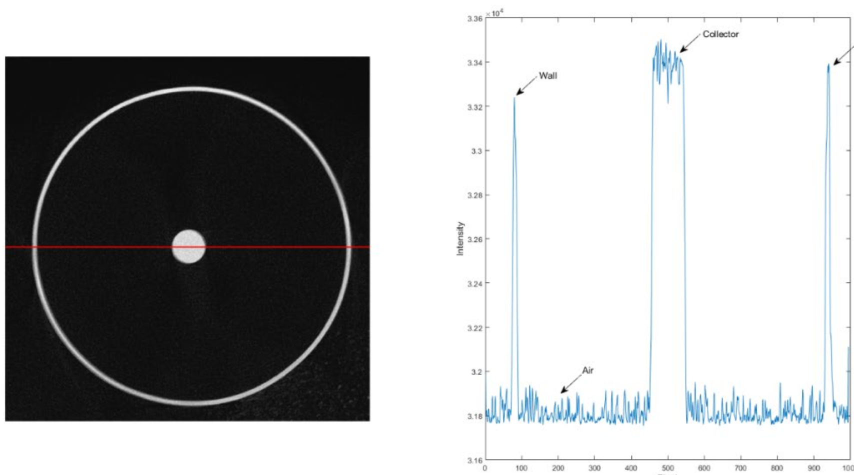

Figure 1. Line profile of central axial slice of Exradin® A3 in Mediso scanner (left) and corresponding C552 and air intensity peaks (right) used to determine segmentation threshold.

The chamber was segmented in Imalytics Preclinical software using the calculated thresholds. The segmented volume yielded the geometric inner air volume after application of a scanner-specific scaling factor. This was found as the ratio of imaged-to-physical lengths of a cylindrical bone mineral density phantom scanned under identical acquisition conditions and with corrections applied for misalignment in the scanner bed. To obtain the sensitive volume, the geometric volume was corrected for regions that do not contribute to charge collection due to electric field inhomogeneities. A two-dimensional COMSOL

Multiphysics simulation of electric field lines in a transverse, central slice of the chamber was used to determine the subtraction volume (Figure 2), which yielded the final sensitive volume of the Exradin® A3.

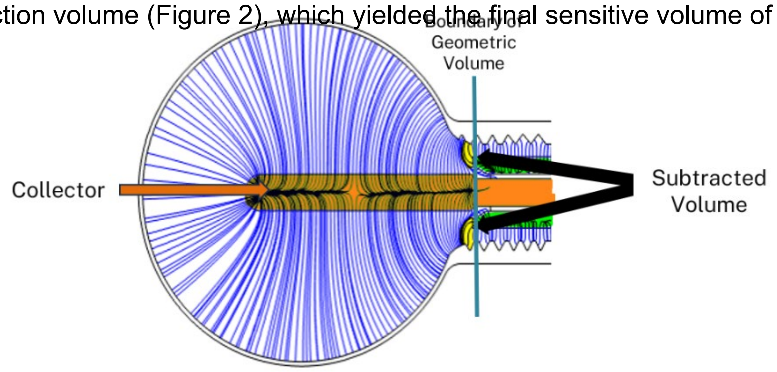

Figure 2. Two-dimensional COMSOL Multiphysics simulation of electric field lines (blue) in a transverse central slice of the A3 ionization chamber, used to correct geometric volume to sensitive volume. The average yellow area was revolved 2π under the assumption of radial symmetry to determine an electric field correction volume to subtract from the geometric volume.

Results:
Table 1. shows the results for each step of the volume determination for each scanner and the contribution of the relative standard uncertainty of this result. All three micro-CT-derived sensitive volumes agreed within their uncertainties and were consistent with the manufacturer's nominal volume and a calculated volume using the ^{60}Co exposure calibration coefficient, as reported by DeWerd et al (2025) (Figure 3). Among the methods compared, micro-CT produced the smallest overall uncertainty irrespective of the type of scanner used. Differences in micro-CT uncertainty were primarily related to voxel size differences in the segmentation and scaling correction. A sample uncertainty budget for the A3 ionization chamber in the Neoscan is shown in Table 2.

Table 1. Comparison of sensitive volume of A3 ionization chamber

	MII Labs	Neoscan	Mediso
Threshold	-218 $\pm$ 0.14%	28308 $\pm$ 1.73%	32546 $\pm$ 0.25%
Segmented Volume (cm^3)	3.595 $\pm$ 0.20%	3.572 $\pm$ 0.23%	3.559 $\pm$ 0.32%
Combined Scaling Factor (in X,Y,Z)	1.013 $\pm$ 0.13%	1.007 $\pm$ 0.12%	1.003 $\pm$ 0.13%
Geometric Volume (cm^3)	3.549 $\pm$ 0.21%	3.547$\pm$ 0.26%	3.548 $\pm$ 0.35%
Electric field correction volume (cm^3)	0.013 $\pm$ 0.07%	0.013 $\pm$ 0.07%	0.013 $\pm$ 0.07%
Final Sensitive volume (cm^3)	**3.536 $\pm$ 0.22%**	**3.534 $\pm$ 0.27%**	**3.535 $\pm$ 0.35%**

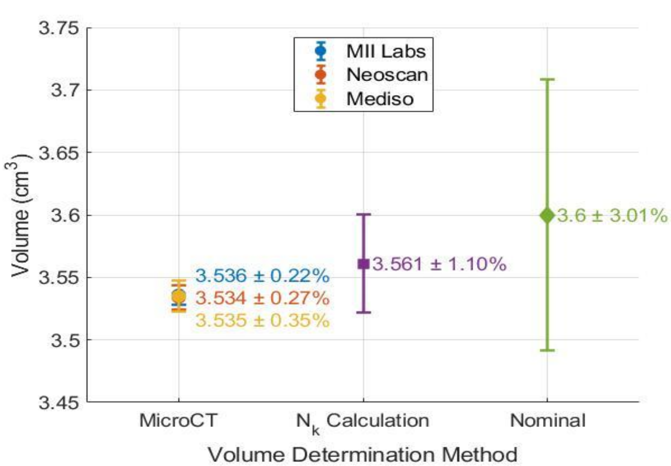

Figure 3. Comparison of Volume Determination Methods. All three methods agree within their standard relative uncertainty with the MII labs microCT yielding the lowest uncertainty.

Table 2. Sensitive Volume Uncertainty Budget for Exradin® A3 Neoscan micro-CT

Source of Uncertainty	Type A (%)	Type B (%)	Comments
Geometric Volume Segmentation			
Threshold Value	0.06		Standard deviation in volume based on threshold values
Region of Interest (ROI)		0.01	Variations in ROI with triangular distribution
Partial Volume of Voxel		0.22	Found using reported voxel size
Reported Voxel Size		0.05	Half last digit reported in dicom header with a rectangular distribution
Micro-CT Scaling Correction			
Scaling Factor	0.12		Standard deviation of scaling in each dimension
Caliper Resolution		0.02	Half of the last significant digit on the display
Electric Field Correction			
Electric Field Subtraction Volume	0.07		Standard deviation based on two electric field subtraction areas
Curve-Fit for Electric Field Streamline		0.002	Change in volume found by varying R^2 values for curve fit
Combined Uncertainty	0.15	0.23	
Standard Uncertainty	0.27		k=1 uncertainty confidence interval
Expanded Uncertainty	0.62		k=2 uncertainty confidence interval

Conclusions: Various micro-CT scanners can be used to non-destructively determine the geometric volume of an ionization chamber, although some scanners offer advantages in image quality leading to lower uncertainties. Additional electric field corrections can yield the sensitive volume of ionization chambers for absolute measurements of the air-kerma.

Relevance to CIRMS: This work is a part of doctoral work of the first author which focuses on improving radiation standards for higher energy photon sources. It relates to the CIRMS mission by presenting a non-destructive method to establish physical standards of measurement. The first author's goal is to become a clinical/academic medical physicist and currently works in a laboratory focused on metrology.

References:

1. L. DeWerd, C. Almeida, O. Araújo, K. Rex Pius Vincent, A. Khan, L. Franco, and R. Lopes. "Determination of the sensitive volume of a spherical ion chamber as a potential primary standard instrument for higher energy photon beams." *Radiation Measurements* 183, 107416 (2025).