

A low-cost iodine phantom for spectral CT quality control: multicentre evaluation of iodine quantification

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Abstract

Objectives:

Feasibility study to develop and evaluate a practical, low-cost iodine phantom framework for assessing reproducibility of iodine quantification in spectral CT quality control across diverse clinical settings and scanner technologies.

Methods:

Two iodine phantoms were independently created using locally available clinical equipment. Iodine inserts, prepared from a 30 mg I/mL stock solution with nominal concentrations of 1–30 mg I/mL, were submerged in water arranged to mimic abdominal geometry. The phantoms were tested on three spectral CT systems—split-filter, dual-source, and photon-counting CT. Iodine maps were reconstructed via clinical workflow, with five ROI measurements along the z-axis per vial. Linearity, bias, relative error, and longitudinal constancy were evaluated.

Results:

Measured iodine concentrations showed strong linearity with nominal values across all systems ($R^2 = 0.9978$ – 0.9993). Regression slopes (1.008–1.099) indicated slight positive bias. Relative errors were highest at low concentrations (~ 1 – 2.5 mg I/mL) and improved at higher levels. The ~ 10 mg I/mL insert measurements remained within $\pm 5\%$ of the mean over 185 and 203 days for each phantom.

Conclusions:

A simple and inexpensive iodine phantom can be constructed locally and implemented reproducibly for spectral-CT iodine-quantification.

Advances in knowledge:

This study presents a feasible, locally constructable phantom framework that provides a complementary approach for multicentre spectral CT iodine quantification quality control and longitudinal constancy monitoring.

Introduction

Spectral CT enables material characterisation using different X-ray spectra with technologies such as dual-source acquisition, rapid kV switching, split-filter techniques, dual-layer detector systems, and photon-counting CT (PCCT). As spectral CT becomes more widely used in routine clinical imaging, quantitative outputs, such as iodine concentration, are increasingly being used to support lesion characterisation, vascular assessment,

contrast optimisation, and follow-up imaging [1], along with qualitative information such as virtual monoenergetic images, virtual non-contrast images, and material-specific maps, including iodine maps [2].

Quality control for spectral CT requires consideration beyond that of conventional single-energy CT image-quality tests. Multi-energy CT systems differ substantially in terms of hardware design, spectral separation, reconstruction algorithms and material decomposition. The AAPM Task Group 299 emphasises that these differences require task-specific QC tests to address image quality, radiation dose, material differentiation, and material quantification [3]. In this context, iodine quantification is a practical and clinically relevant endpoint for routine spectral CT QC because it directly reflects the performance of the entire acquisition, reconstruction, and post-processing chain.

The iodine quantification performance has been investigated in several studies. Prior studies have demonstrated that iodine detectability and quantification depend on scanner technology, phantom size, iodine concentration, dose level, and reconstruction method [4–6]. Dose and reconstruction settings also influence virtual monoenergetic image quality and iodine quantification performance, particularly at low iodine concentrations. [7].

Several dedicated and commercial phantom solutions have been proposed for spectral-CT QC. Commercial multi-energy CT phantoms provide tissue-equivalent materials and inserts containing iodine, calcium, blood-equivalent materials, and adipose-equivalent materials for calibration. They can support material discrimination, quantitative accuracy testing and inter-scanner consistency assessment. Practical DECT QC programs have also been described using phantoms with clinically relevant materials and concentrations, combined with standardised acquisition, reconstruction, and automated analysis workflows.

However, dedicated commercial or custom-manufactured phantoms may not be available in all clinical settings due to cost, procurement barriers, and limited local access. The US FDA has proposed a PMMA/Lucite phantom for the objective assessment of iodine-specific material quantification in contrast-enhanced spectral CT. This design is well-suited for formal device characterisation but requires controlled construction using machined materials and predefined target structures. Therefore, a locally assembled water-bottle phantom may provide a complementary approach focused on practical implementation, longitudinal constancy monitoring, and multicentre feasibility rather than traceable accuracy assessment.

Within the broader context of the ongoing update of IAEA Human Health Series No. 19 on computed tomography quality assurance, this multicentre study aimed to develop and evaluate a low-cost iodine phantom framework for spectral CT quality control. Two phantoms were independently constructed using locally available clinical supplies, consisting of iodine inserts submerged in a water background with nominal iodine concentrations spanning approximately 1–30 mg I/mL. The practical implementation of the framework was assessed across different clinical environments and spectral CT technologies by evaluating the iodine quantification linearity, bias, and longitudinal stability over time.

Methods

3.1 Phantom Framework and Independent Construction

An affordable iodine phantom framework was developed in accordance with the quality control principles for multi-energy CT proposed in the AAPM Task Group Report 299. To assess reproducibility across facilities, two setups were independently constructed in Bogota, Colombia, and Melbourne, Australia, using the same general methodology and locally available clinical supplies.

The framework used a clustered bottle arrangement with internal iodine inserts submerged in a water background to approximate the adult abdominal geometry. The bottles were arranged in an ellipsoidal cluster and were fixed (Fig. 1). Each bottle contained water as the background material, and iodine-containing vials were positioned internally to allow a quantitative assessment of the iodine maps.

Iodine solutions were prepared from clinically available iodinated contrast media using a two-stage dilution process to obtain nominal iodine concentrations of approximately 1–30 mgI/mL. The two phantoms differed slightly in terms of the number and range of iodine concentrations used. Phantom #1, constructed in Bogotá, contained four iodine inserts. Phantom #2, constructed in Melbourne, incorporated eight iodine inserts over a wider concentration range.

In Phantom #1, predefined volumes of the 30 mg I/mL parent stock solution (0.73, 2.52, 5.00, and 9.00 mL) were diluted to a final volume of 14 mL, yielding nominal concentrations of 1.1, 5.4, 10.7, and 19.3 mg I/mL, respectively. In Phantom #2, the stock volume was calculated for each desired final concentration, yielding nominal concentrations of 1.0–30.0 mg I/mL.

A summary of the nominal iodine concentrations is presented in Table 1. A step-by-step construction and dilution protocol, including specific stock volumes, vial volumes, bottle arrangement, and ROI analysis guidance, is provided in the Supplementary Material.

Table 1
Nominal iodine concentrations (mg I/mL) for Phantoms #1 and #2.

Vial	Phantom #1 (Bogota)	Phantom #2 (Melbourne)
1	1.1	1.0
2	5.4	2.5
3	10.7	5.0
4	19.3	10.0
5	-	15.0
6	-	20.0
7	-	25.0
8	-	30.0

3.2 Spectral CT Technologies and Protocol

Scans were performed on three spectral CT systems representing different hardware architectures: single-source CT with a split filter, dual-source CT, and PCCT. The acquisition parameters are listed in Table 2.

Phantom #1 was scanned using split-filter CT and PCCT scans. Phantom #2 was scanned using a dual-source CT. All centres used their locally implemented abdomen/pelvis spectral CT protocol. The phantom was positioned centrally within the CT gantry, and the bottle cluster was arranged to maintain a consistent cross-sectional geometry. Each acquisition covered the full length of the iodine inserts and the surrounding water background. Iodine maps were reconstructed using the clinical spectral post-processing workflow available at each site. Where available, the material decomposition parameters used for iodine-map reconstruction were recorded as part of the protocol. In this study, this corresponded to the relative contrast medium ratio (RelCM), a protocol-specific parameter related to the relative iodine contrast between spectral datasets and effective spectral separation used for material decomposition.

Repeated phantom scans were acquired to evaluate the measurement constancy over time using split-filter and dual-source computed tomography (CT) scanners. Phantom #1 was scanned six times over 203 d and Phantom #2 was scanned seven times over 185 d. These acquisitions were performed at approximately baseline, one month, three months, and six months, with additional intermediate scans depending on the scanner availability. A single scan was performed on the PCCT using phantom #1.

All scanners were in routine clinical operation and were subject to institutional quality assurance, consistency testing, preventive maintenance, and local regulatory performance requirements at the time of the acquisition.

Table 2
Dual-energy abdomen/pelvis CT scan protocol parameters.

Parameter	System 1	System 2	System 3
Spectral CT technology	Split-filter	Dual-source	PCCT
Location	Bogota, Colombia	Melbourne, Australia	Vienna, Austria
Scanner model	SOMATOM X.cite	SOMATOM Drive	NAEOTOM Alpha
Tube potential	AuSn120	100 kV / Sn140 kV	120 kV
Effective mAs	395	178	150
Pitch	0.3	0.6	0.8
Rotation time (s)	0.3	0.33	0.5
Collimation	128 × 0.6 mm	64 × 0.6 mm	144 × 0.4 mm
Iterative reconstruction	ADMIRE 3	ADMIRE 3	ADMIRE 3
CTDIvol (mGy)	8.15	13.0	11.9
RelCM / material decomposition parameter	1.57	2.24	2.18

3.3 Image Analysis

Iodine concentration was measured using a clinical spectral CT workstation by placing circular ROIs (60% of vial diameter) within each iodine vial to reduce edge artefacts and partial-volume effects. Five ROI measurements along the z-axis were averaged. Accuracy was assessed against AAPM TG 299 criteria: absolute error ≤ 0.5 mg I/mL or relative error $\leq 20\%$. Absolute error is the difference between measured and nominal concentrations; relative error is the absolute error divided by nominal concentration (%). Longitudinal constancy was evaluated as the percentage variation of average iodine concentration relative to the mean across repeated scans. Linearity and reproducibility were analyzed via linear regression with free intercept; coefficient of determination, slope, intercept, and root mean square error were reported. Descriptive statistics (mean, standard deviation, absolute and relative errors) were calculated per concentration and scanner. No formal hypothesis testing was performed, focusing instead on feasibility, accuracy, linearity, and constancy.

Results

4.1 Dataset and phantom implementation

The final analysis involved two independently constructed iodine phantoms, three clinical centers, three spectral CT technologies, and 14 scan sessions. Phantom #1 was assessed with split-filter CT and PCCT, while Phantom #2 was evaluated using dual-source CT. Longitudinal data were available for split-filter and dual-source CT, with six and seven scans over 203 and 185 days, respectively; PCCT had one scan session. Nominal iodine concentrations ranged from 1.0 to 30.0 mg I/mL. For each vial and scan, five ROI measurements along the z-axis were averaged. Table 3 summarizes dataset characteristics and quantitative metrics.

4.2 Iodine quantification linearity

The measured iodine concentration showed a strong linear relationship with the nominal iodine concentration for all three scanners (Fig. 2). The coefficients of determination were high for all evaluated spectral CT systems, with R^2 values of 0.9993 for split-filter CT, 0.9992 for dual-source CT, and 0.9978 for PCCT.

Table 3
Summary of the dataset and iodine quantification metrics.

Centre	Spectral CT technology	Phantom used	Scan sessions	Follow-up	Slope	Intercept, mg I/mL	R ²	RMSE, mg I/mL
Bogota	Split-filter	Phantom #1	6	203 days	1.099	0.458	0.9993	1.53
Melbourne	Dual-source	Phantom #2	7	185 days	1.008	1.011	0.9992	1.16
Vienna	PCCT	Phantom #1	1	Not applicable	1.071	0.350	0.9978	1.16

The regression slopes ranged from 1.008 to 1.099, with the lowest slope observed for dual-source CT and the highest for split-filter CT. The regression intercepts ranged from 0.350 to 1.011 mgI/mL. The overall deviation

from the nominal iodine concentrations, expressed as the root mean square error (RMSE), ranged from 1.16 to 1.53 mg I/mL (Table 3).

4.3 Accuracy relative to nominal iodine concentration

The relative quantification error was highest at low iodine concentrations and decreased as the iodine concentration increased (Fig. 3). At the lowest iodine concentration (approximately 1.0–1.1 mg I/mL), all systems showed limited accuracy. The relative errors were 76.3% and 48.8% for the split-filter CT and 45.5% for the dual-source CT, split-filter CT, and PCCT.

At 2.5 mg I/mL, evaluated only in Phantom #2, the relative error remained above the AAPM TG 299 relative error criterion, with a mean error of 32.1%. Accuracy improved at intermediate concentrations. At 5.0–5.4 mg I/mL, the relative errors were 19.7% for dual-source CT, 15.4% for split-filter CT, and 5.9% for PCCT, meeting or approaching the 20% TG 299 threshold.

For concentrations of approximately 10 mg I/mL and above, all evaluated measurements remained within the TG 299 relative-error criteria. The relative errors were 15.9% for dual-source CT at 10 mg I/mL, 17.2% for split-filter CT at 10.7 mg I/mL, and 15.1% for PCCT at 10.7 mg I/mL. At higher iodine concentrations, the relative errors further decreased, reaching 3.7% at 25–30 mg I/mL for dual-source CT and 8.0–11.6% at 19.3 mg I/mL for both split-filter and PCCT scanners.

4.4 Longitudinal constancy

Longitudinal assessment showed stable iodine quantification over time for both phantoms (Fig. 4). For the ~10 mg I/mL insert, measured values stayed within $\pm 5\%$ of the series mean for both split-filter and dual-source CT.

On dual-source CT, Phantom #2's 10 mg I/mL insert averaged 11.6 mg I/mL across seven scans, with a maximum deviation of 2.47% at 185 days. On split-filter CT, Phantom #1's 10.7 mg I/mL insert averaged 12.54 mg I/mL over six scans, with a maximum deviation of 4.28% at 203 days. Despite greater variability on split-filter CT, all results remained within the $\pm 5\%$ constancy threshold.

Discussion

In this study, we developed and evaluated a simple and low-cost iodine phantom framework for spectral CT quality control. The design uses vials with contrast material submerged in bottles, allowing construction using locally available clinical supplies without the need for specialised manufacturing. To evaluate the feasibility, two phantoms were independently built in Bogotá and Melbourne using the same general methodology.

The phantoms were scanned using three different spectral CT technologies, which demonstrated consistent quantitative responses. Iodine quantification showed high linearity across the concentration ranges evaluated, with R^2 values approaching unity. A minor positive bias was detected, suggesting that the phantom should not

be considered a traceable-calibration standard. Nevertheless, its significant linearity and longitudinal stability support its application as a practical tool for implementation.

Accuracy was concentration-dependent. The largest relative errors occurred at low iodine concentrations, particularly around 1–2.5 mg I/mL, where small absolute deviations produced large relative errors, and the measurements were more sensitive to the image noise and material decomposition uncertainty. From approximately 5 mg I/mL, the measurements generally approached or met the AAPM TG 299 relative error criterion, whereas concentrations around 10 mg I/mL and above consistently satisfied this criterion. The longitudinal results further supported the phantom's utility for constancy assessment, with the approximately 10 mg I/mL insert remaining within $\pm 5\%$ of the series mean over the follow-up period for both phantoms #1 and #2.

The regression intercepts differed between the systems, which likely reflects differences in scanner calibration, reconstruction settings, material decomposition, and concentration-dependent bias. A free-intercept model was retained because the purpose of the analysis was to describe both the proportional response and the systematic offset. A forced-zero regression may be useful as a secondary analysis in future studies, particularly if iodine concentrations are independently verified.

The rationale for this type of test is consistent with AAPM TG 299, which emphasises that multi-energy CT quality control requires task-specific assessment of material quantification beyond conventional CT image quality test [3]. Iodine quantification is a clinically relevant endpoint because it reflects the combined performance of acquisition, reconstruction, and material decomposition processes. The proposed framework is also aligned with recently proposed phantom-based methods for iodine-specific quantification in spectral CT. One such method describes a PMMA/Lucite phantom with iodine targets in water, allowing users to define nominal iodine concentrations according to the intended clinical application and evaluate performance by comparing CT-derived measurements with a predetermined reference truth. However, this approach is more suited to formal device characterisation, whereas the present design prioritises local constructability and routine clinical feasibility.

Our findings are consistent with those of previous studies. Jacobsen et al. evaluated iodine solutions from 0.03 to 2.0 mg I/mL across multiple dual-energy CT systems and reported that the limit of quantification depended on scanner and phantom size, reaching 0.20–1.0 mg/mL in large phantoms [7]. Li et al. used a commercial multi-energy CT phantom with iodine-in-water inserts from 0.2 to 15.0 mg/mL and iodine-in-blood inserts from 0.5 to 5.0 mg/mL, reporting poorer accuracy below 0.5 mg/mL and improved performance above this level [8]. Similarly, Green et al. proposed a practical DECT QC program using iodine inserts of 0.5, 1, 2, and 5 mg/mL for routine monitoring and trend analysis [5]. Compared with these studies, the present phantom covers a broader iodine range of approximately 1–30 mg I/mL and emphasises low-cost local fabrication and international reproducibility.

In this study, RelCM was 1.57 for split-filter CT, 2.24 for dual-source CT, and 2.18 for PCCT. Higher RelCM generally favors iodine decomposition, possibly explaining lower bias in dual-source CT and PCCT. However, RelCM is protocol-specific, influenced by factors like phantom size, beam hardening, scatter, noise, reconstruction, and calibration. Thus, these values serve as supportive protocol information, not definitive proof of spectral performance differences.

This study had some limitations. First, dilution uncertainties were not propagated, and iodine concentrations were not independently verified; therefore, nominal concentrations should be interpreted as calculated rather than as traceable reference values. Second, fabrication challenges, such as air bubbles, needle gauge selection, and adhesive compatibility, may vary with locally available materials, requiring site-specific optimisation. Third, longitudinal analysis reflects combined system and phantom constancy because scanner drift, software updates, or changes in material decomposition may affect the measured iodine concentration. Fourth, although three spectral CT architectures were included, all systems were from a single vendor. Finally, no commercial or traceable iodine phantoms were scanned as comparators; therefore, the observed positive bias could not be attributed solely to the locally constructed design of the phantom. Further validation across additional vendors and platforms and independent verification of iodine concentrations are required.

Conclusion

A low-cost iodine phantom framework for spectral CT quality control was developed and evaluated in three clinical settings. The phantom demonstrated highly linear iodine quantification and stable longitudinal performance, indicating its utility as a practical tool for local implementation and consistency monitoring in clinical practice. This framework should be regarded as complementary to commercial or traceable reference phantoms, especially in centres seeking an accessible method for routine iodine quantification and quality control. Further validation across additional vendors and platforms and independent verification of iodine concentrations are necessary.

Declarations

Competing Interests:

The authors declare that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

Ethics approval:

Not applicable. This phantom-based study did not involve human participants, patient data, or identifiable human images.

Consent to participate:

Not applicable

Consent for publication:

Not applicable

Data Availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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Author Contribution

B. N. and B. Z contributed to the conceptualisation and methodology of the study, phantom preparation, experimental setup, data acquisition, data curation, formal analysis, visualisation, drafting of the original manuscript, and review and editing of the final manuscript. K. M. and M. M. contributed to the conceptualisation and methodology of the study, technical interpretation of the results, supervision, and manuscript review and editing. T. V. contributed to methodology, supervision, drafting support, manuscript review, and editing. O. JP. contributed to phantom preparation, experimental setup, data acquisition, and manuscript review and editing. L. L. contributed to phantom preparation, experimental setup, image acquisition, data acquisition, and manuscript review and editing. B. N. contributed to the experimental setup, data acquisition, data curation, and manuscript review and editing. V. B. contributed to the methodology and manuscript review and editing. C. M contributed to supervision, project administration, manuscript review, and editing.

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9. Statements & Declarations

Figures

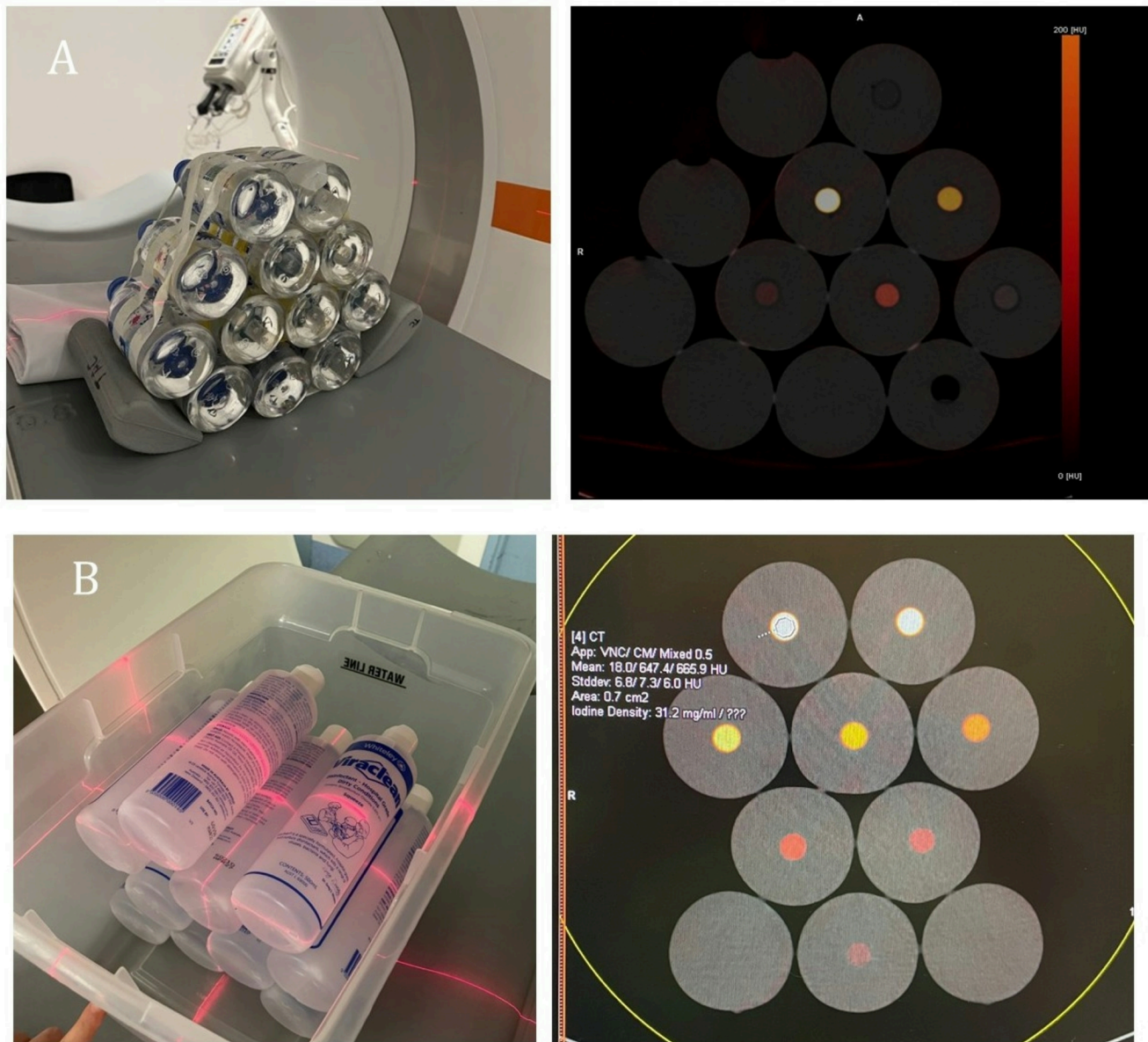


Figure 1

Locally constructed iodine phantom setup for spectral CT quality control. The phantom consisted of an ellipsoidal cluster of water-filled bottles containing iodine. The corresponding iodine map illustrates the distribution of iodine-containing inserts within the water background, which was acquired using the same clinical spectral CT protocol and analytical approach. A) Phantom# 1.; b) Phantom #2.

Alt text: Two locally constructed iodine phantom configurations are shown with corresponding iodine maps. Phantom 1 uses a clustered arrangement of water bottles, while Phantom 2 uses bottles positioned in a plastic container.

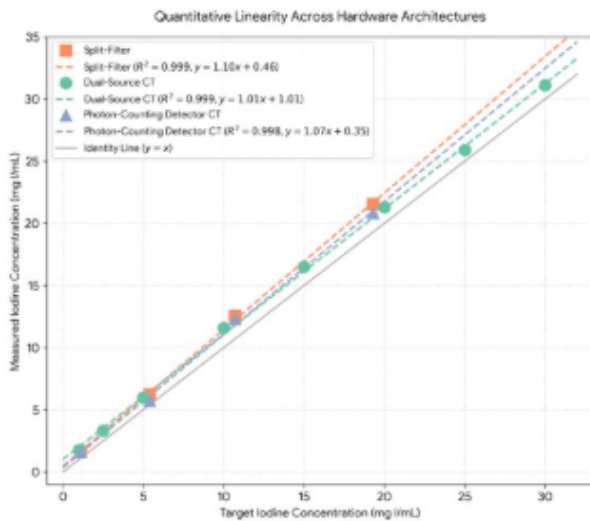


Figure 2

Linearity of iodine quantification was high across three international centers using split-filter, dual-source, and PCCT spectral CT technologies. The scatter plot shows measured versus nominal iodine concentrations with scanner-specific linear regression fits (dashed lines) closely matching the identity line (solid gray), all achieving R^2 values near or above 0.998.

Alt text: Scatter plot of measured versus nominal iodine concentration for split-filter, dual-source and photon-counting CT. All systems show a near-linear response, with regression lines close to the identity line.



Figure 3

Relative quantification errors for split-filter, dual-source, and PCCT were compared against the AAPM TG 299 20% error threshold. Accuracy was lower at iodine concentrations near 1 mg I/mL and 2.5 mg I/mL. Concentrations around 5 mg I/mL and higher generally met or approached the criterion, while those at approximately 10 mg I/mL and above consistently complied across all systems.

Alt text: Bar chart comparing relative iodine quantification error across scanner technologies and concentration ranges. Error is highest at low iodine concentrations and decreases at approximately 5 milligrams iodine per millilitre and above.

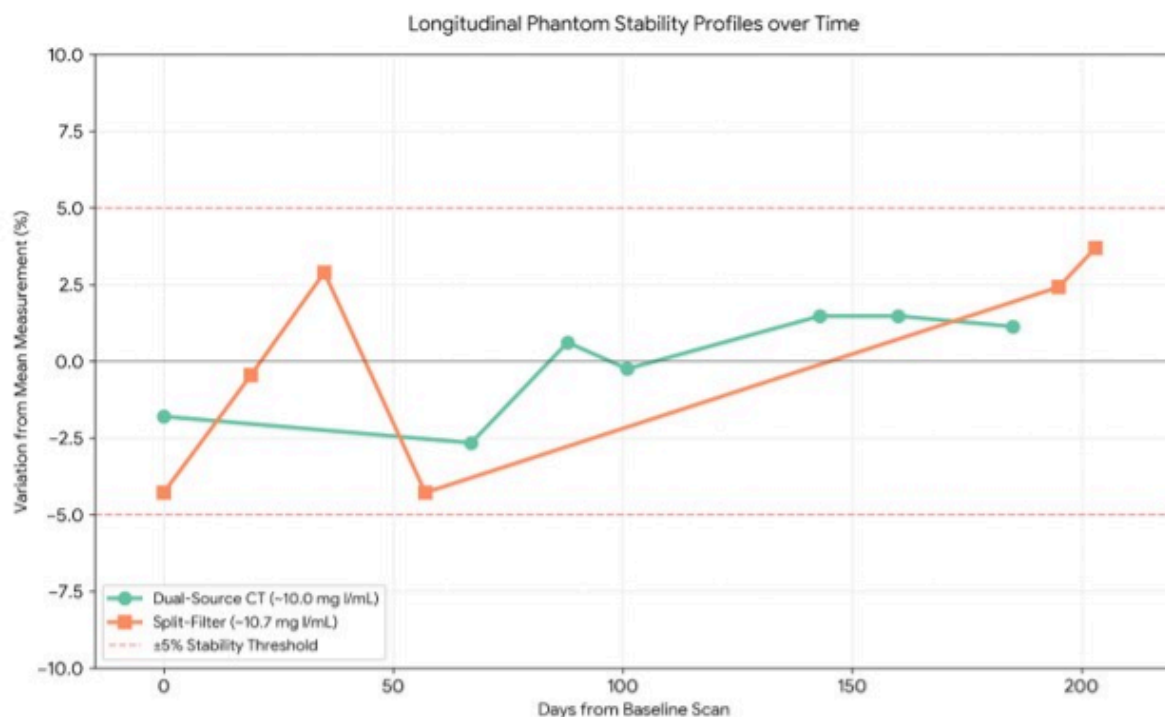


Figure 4

Iodine quantification for the ~10 mg I/mL insert remained stable over time in both phantoms (Phantom #1 on split-filter CT and Phantom #2 on dual-source CT), with variations within $\pm 5\%$ of the mean. Dashed lines mark this stability threshold in the plot.

Alt text: Line plot showing longitudinal percentage variation for the approximately 10 milligrams iodine per millilitre insert. Measurements for split-filter and dual-source CT remain within the plus or minus 5 percent stability threshold.

Supplementary Files

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- [Supplementarymaterial.docx](#)