

Influence of CT Tube Replacement and System Parameter Update on Reconstructed CT Values and Electron Density Conversion Curves in Radiotherapy Treatment Planning Systems

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Abstract

Objective

Large-aperture positioning CT is a core device for radiotherapy simulation, target delineation, and accurate dose calculation. Replacement of the X-ray tube, followed by subsequent system parameter updates (including software version upgrade, reconstruction algorithm adjustment, and detector gain calibration), may alter the X-ray energy spectrum and image reconstruction characteristics, thereby inducing systematic drift of CT numbers (Hounsfield Units, HU) and disturbing the accuracy of CT-relative electron density (CT-RED) and CT-mass density (CT-MD) conversion curves in treatment planning systems (TPS). This study aimed to quantify CT number drifts in multiple tissue-equivalent phantoms before and after tube replacement and system parameter updates using a Philips Big Bore CT 16 scanner, to evaluate the detection efficacy of conventional AAPM TG66 image quality indicators for such occult drift, to reconstruct density conversion curves for Eclipse and Tomo TPS, and to establish a standardized quality control workflow.

Methods

Fault records and the tube replacement process from August 2023 to January 2024 were analyzed. Tube replacement was performed on January 13, 2024, followed by standard acceptance tests including position calibration, focus correction, long-tube conditioning, and air scan. System software was upgraded from V3.6 to V4.8 on October 18, 2024, with resetting of reconstruction filter parameters, detector gain coefficients, and air baseline. All CT value measurements, curve reconstructions, and dosimetric verifications were performed after the software upgrade, representing the combined effect of “tube replacement + system parameter update”. Image quality was tested with a Catphan504 phantom according to AAPM TG66. CT value changes in 8 standard materials (air, polystyrene, water, LDPE, PMP, acrylic, Delrin, Teflon) before and after the intervention were compared using paired t-tests with Bonferroni correction. CT-RED curves (standard and brain-specific) for Eclipse and a CT-MD curve for Tomo were reconstructed using a CIRS-062M phantom containing 12 tissue-equivalent materials. Accuracy of the new curves was validated by heterogeneous phantom planar dose verification and real patient plan QA.

Results

All conventional image quality indicators remained within TG66 tolerances after the intervention. Systematic CT drifts were observed in 7 of the 8 materials except water ($P = 0.12$, not significant), with drifts ranging 10–30 HU for most materials; Teflon showed a -63 HU drift ($P < 0.001$) and air a $+33$ HU drift ($P < 0.001$). Two CT-RED curves for Eclipse and one CT-MD curve for Tomo were successfully constructed, all with $R^2 > 0.99$. Dosimetric verification showed 3 mm/3% Gamma passing rates for

Eclipse $\geq 98.9\%$, mean point-dose deviation for Tomo 0.76%, and real patient plan QA passing rates $> 98\%$ with no significant differences before vs. after intervention ($P > 0.05$).

Conclusion

CT tube replacement and subsequent system parameter updates did not impair conventional TG66 image quality indicators, but induced systematic, material-dependent CT number drifts that cannot be detected by routine water-phantom uniformity tests. Re-measurement of multi-material CT baselines and mandatory reconstruction of density conversion curves are required. A four-level quality control process (air calibration, multi-material CT baseline measurement, curve reconstruction, and dosimetric verification) should be enforced after tube replacement or major software upgrades.

1 Introduction

Precision radiotherapy relies on CT simulation images for accurate target delineation, organ-at-risk definition, and dose calculation. CT number (Hounsfield Unit, HU) is a core quantitative parameter that links image grayscale to tissue physical density and serves as a key input for advanced dose algorithms such as the Anisotropic Analytic Algorithm (AAA) and Monte Carlo methods in treatment planning systems (TPS) ^[1–3]. The CT-relative electron density (CT-RED) and CT-mass density (CT-MD) conversion curves are the critical calibrations that map pixel CT values to electron density and mass density of human tissues; the fitting accuracy directly determines the dose delivery accuracy of intensity-modulated radiotherapy, volumetric modulated arc therapy, and stereotactic body radiotherapy (SBRT) ^[4–5].

The X-ray tube is a high-loss core component of large-aperture positioning CT, with a clinical service life of typically 5–10 years. Aging, anode sparking, and high-voltage package failures eventually necessitate tube replacement ^[6]. After replacement, the new tube inevitably differs from the old one in anode target material, electron beam focusing characteristics, inherent filtration thickness, and X-ray energy spectrum distribution. These differences alter the relative contributions of photoelectric effect and Compton scattering for tissues with different atomic numbers, leading to non-uniform CT number drifts for the same tissue-equivalent materials ^[7–8]. If such drifts are ignored and the old density conversion curves are retained, dose calculation errors of 1%–3% may occur in bone, metal implants, and low-density lung regions, posing non-negligible clinical safety risks for high-precision treatments such as SBRT ^[9].

Current international quality control guidelines (AAPM TG66, IAEA 31, IPEM 91) only require routine image quality re-testing after major CT maintenance (including tube replacement), but do not provide standardized procedures for CT number baseline calibration, quantitative verification with multi-material phantoms, density conversion curve reconstruction, or dosimetric verification ^[10–12]. In clinical practice, it is common to perform only routine image QC while omitting quantitative CT calibration and curve reconstruction. Although IPEM Report 81 suggests that conversion curves should be re-established

when CT number changes exceed 10–20 HU, this threshold is empirical and lacks actionable protocols. Thus, existing guidelines are inadequate for detecting occult CT number drifts, and more specific, quantifiable QC processes are needed.

Moreover, current radiotherapy QC research has largely focused on advanced technologies such as AI-based detection of cone-beam CT six-dimensional positioning errors and automatic organ segmentation. Basic QC and dosimetric traceability studies after replacement of core CT hardware components are scarce, and single-center studies with complete process data and statistical validation are lacking. In particular, tube replacement and subsequent system parameter updates are often performed sequentially or simultaneously as combined interventions, but the independent contributions of each factor are rarely separated, and complete closed-loop evidence from hardware change to dose verification is absent.

This study therefore performed a hierarchical investigation across five dimensions (macroscopic image quality, microscopic CT number drift, density curve reconstruction, phantom dose verification, and clinical patient plan verification) based on a real-world clinical process of CT tube replacement and system parameter updates. The objectives were: (1) to quantify CT number drift patterns for tissue-equivalent materials with different atomic numbers before and after tube replacement and system parameter update; (2) to assess the ability of conventional AAPM TG66 image quality indicators (especially water phantom uniformity) to detect occult CT drifts; (3) to distinguish curve differences between thoracic and cranial scanning protocols and establish a multi-TPS adaptive density curve reconstruction method; (4) to complete dosimetric closed-loop verification through phantom dose verification and real patient plan QA; and (5) to propose an actionable standardized QC process to supplement the deficiencies of existing international guidelines and provide evidence-based references for radiotherapy department equipment operation and precision radiotherapy QC.

2 Methods

2.1 Equipment Background and Fault Maintenance Process

A Philips Big Bore CT 16 large-aperture simulation CT (Philips Healthcare, Netherlands) was used in this study. The equipment was installed in the radiotherapy department of our hospital and dedicated to patient simulation. It was put into clinical use in 2015, and by 2023 it had approached its design tube life (approximately 8–10 years). Starting in August 2023, the equipment experienced frequent faults including startup failures, scanning interruptions, and sparking. Tube aging was confirmed, and a new X-ray tube was replaced on January 13, 2024. The fault logs and maintenance records from August 2023 to January 2024 were completely reviewed, and the phenomena, engineering analyses, and treatment measures were recorded to provide a full equipment status baseline for subsequent studies on tube replacement and CT number drift. Table 1 summarizes the major fault events before CT tube replacement.

Table 1
Major Fault Events Before CT Tube Replacement

Fault Time	Fault Phenomenon	Treatment Measures
2023.08.14	Gantry startup failure with unclosed relay	Startup operation was corrected, and normal operation was restored
2023.11.10	Scanning error with anode sparking	High-voltage plug was cleaned for temporary recovery
2023.12.09	Anode high-voltage package failure	Anode high-voltage package was replaced
2023.12.13	Cathode high-voltage package failure	Cathode high-voltage package was replaced with insulating oil filled
2024.01.13	Tube aging with abnormal exposure	A brand-new X-ray tube was replaced

2.1.1 Progressive Fault Manifestations and Tube Aging Mechanism

The equipment faults showed a progressive deterioration pattern. Initially, random “X-ray system cannot comply” errors occurred during scanning, causing interruption; the system could be temporarily restored by restarting, but errors recurred under high-condition exposure or continuous scanning. Over time, the error frequency increased significantly and could not be eliminated by restarting. System self-tests indicated high-voltage abnormalities, accompanied by slight internal abnormal noises. Although short-term operation was still possible, stability was poor, image noise increased, high-contrast resolution decreased, and sparking failure occurred during long-tube conditioning.

These manifestations were fundamentally caused by physical degradation of the CT tube. The CT tube consists of a cathode filament and a rotating anode target sealed in a high-vacuum envelope. X-rays are generated when electrons emitted from the heated filament bombard the anode target at high speed under an anode high voltage (80–140 kV). Long-term operation under extreme conditions (high voltage, high current, high vacuum, high rotation speed of ~ 10,000 rpm) inevitably leads to: (1) cracking, roughening, and micropore formation on the anode target surface due to prolonged electron bombardment, altering the X-ray energy spectrum (typically hardening or softening); (2) decreased vacuum allowing trace gas release, increasing sparking probability especially during high-condition exposure or conditioning; (3) gradual evaporation and thinning of the filament, causing unstable emission current; and (4) wear of rotating bearings reducing anode speed and heat dissipation. These degradations manifest as systematic CT number drift (especially for high-Z materials), increased image noise, reduced high-contrast resolution, and degraded overall image quality.

2.1.2 Hierarchical Fault Diagnosis Strategy

A step-by-step hierarchical diagnosis strategy was applied to locate the fault source.

Step 1: Intermittent sparking → high-voltage plug/cable insulation problem.

The phenomenon was that errors were triggered under high-kV/mA exposure and could be recovered by restart. Manual exposure tests in engineer mode (80 kV/200 mA → 120 kV/400 mA) showed frequent errors at 120 kV/400 mA, indicating insulation degradation. Inspection of the high-voltage anode cable and plug revealed some dust and oil without carbonization; insulation resistance was low and unstable. Cleaning and applying insulating silicone grease temporarily eliminated sparking, but the instability was exacerbated by existing tube aging and target damage.

Step 2: Persistent high-voltage error → high-voltage package failure.

As faults progressed, errors became persistent and could not be eliminated by restart. Self-test codes directly indicated high-voltage abnormalities with internal noise. Monitoring showed > 8% fluctuation in anode high-voltage package output and abnormal filament current feedback. An exchange test with a known-good package transferred the fault, confirming internal insulation aging of the high-voltage packages. After replacing both anode and cathode packages, short-term operation was possible, but image quality was not fully restored, suggesting residual tube problems.

Step 3: Image and conditioning problems remain after high-voltage component replacement → tube aging.

After plug cleaning and high-voltage package replacement, increased image noise, reduced spatial resolution, and conditioning sparking persisted. Catphan504 tests showed spatial resolution decreased from 7.5 lp/cm to 7.0 lp/cm; CT number uniformity remained within TG66 tolerance (± 20 HU), but comparison with baseline revealed systematic drift: air CT number increased from – 1000 HU to – 967 HU (positive drift), while Teflon (high-Z) decreased from 1001 HU to 938 HU (negative drift). This indicated a change in tube energy spectrum, causing non-uniform CT number shifts for materials with different atomic numbers, with high-Z materials most sensitive. The roughened anode target enlarged the effective focus, reducing spatial resolution; decreased tube vacuum caused ionization of residual gas, and conditioning sparking could not be eliminated even after accurate position calibration. Cumulative exposure time exceeded the design life (approx. 100,000 seconds). By exclusion (high-voltage plug cleaned, packages new, all calibrations performed), the only remaining fault source was the tube itself.

2.2 Phantom Equipment and Scanning Protocol

Image quality phantom: Catphan504 standard CT image quality phantom, used to measure spatial resolution, low-contrast CNR, slice thickness accuracy, and CT number uniformity according to AAPM TG66. This phantom also contains a CT number linearity module consisting of 8 standard materials (air, polystyrene, water, LDPE, PMP, acrylic, Delrin, Teflon) for quantitative comparison of CT number drift before and after tube replacement.

Electron density phantom

CIRS-062M tissue-equivalent electron density phantom, containing 12 human tissue-equivalent materials (lung inhale, lung exhale, adipose, breast, water, muscle, liver, BONE200, BONE800, BONE1250, bone core, titanium), used for CT-RED curve fitting.

Density verification phantom

CheesePhantom cylindrical phantom (30 cm diameter, 18 cm thickness) with 8 gradient density rods (mass density range 0.29–1.82 g/cm³), used for CT-MD curve construction and point dose verification.

Heterogeneous dose phantom: PTW T40037 heterogeneous phantom with PMMA, tissue-equivalent, lung-equivalent, and bone-equivalent inserts, used for planar dose Gamma verification.

Accelerator and detectors

Varian VitalBeam medical linear accelerator, Octavius 1500 planar detector, A1SL precision ionization chamber, Octavius 4D phantom, ArcCheck phantom.

Scanning parameters: All scans were performed with a unified clinical standard protocol: 120 kV, 280 mAs, Filter Sharp (C) reconstruction filter, Enhancement 0.25. A dedicated brain protocol (head scan) was used for brain acquisitions, with other parameters kept the same..

2.3 Data Acquisition Time Points and Confounding Factor Control

The CT equipment underwent tube replacement on January 13, 2024, followed by standard acceptance procedures (position calibration, focus correction, conditioning, air scan). Due to departmental workflow, the equipment continued normal operation until October 2024 with no hardware changes. On October 18, 2024, the system software was upgraded from V3.6 to V4.8; after the upgrade, factory engineers performed debugging and all calibrations. All CT number measurements, density curve reconstructions, and dosimetric verifications reported in this study were performed after the software upgrade (October 18–20, 2024). Therefore, the results reflect the combined effect of “tube replacement + software upgrade/parameter reset” and cannot be independently attributed to tube replacement alone. In real clinical practice, tube replacement is often accompanied by system parameter resets or software updates, so the findings have direct practical value .

2.4 Post-replacement Acceptance Test Process

After tube replacement, a stepwise acceptance workflow was executed to ensure stable operation of the new tube and complete resolution of faults. This workflow, together with subsequent density curve reconstruction and dosimetric verification, formed a complete quality control loop.

First, dynamic balance testing was performed by rotating the anode to about 10,000 rpm to monitor vibration and abnormal noise and confirm proper bearing alignment. Filament preheating and correction were then carried out to remove adsorbed gas and adjust control parameters based on emission current

feedback, ensuring stable electron beam current at different tube currents. Third, tube conditioning was performed with a stepwise voltage ramp (from 80 kV/50 mA up to 120 kV/400 mA) with repeated exposures and cooling, to allow controlled ionization of residual gas and uniform heating of the target surface, avoiding severe sparking at high voltage. After conditioning, micron-level position calibration (X, Y, Z axes) was performed by adjusting fixing screws (16 ticks per turn) to precisely align the focal spot projection with the detector center. Collimator calibration and focus correction were then completed to match the X-ray beam boundaries with the detector array and update correction parameters to restore high spatial resolution. After these geometric and electrical calibrations, an air scan was performed without any phantom to acquire the detector background response, establish new zero and gain baselines, and restore the air CT number to -1000 HU, thereby correcting the systematic CT number drift caused by the change in tube energy spectrum. Subsequently, Catphan504 phantom tests were performed according to AAPM TG66: spatial resolution ≥ 7 lp/cm, low-contrast CNR ≥ 0.64 , slice thickness deviation $\leq \pm 0.5$ mm, CT number uniformity $\leq \pm 20$ HU, and acceptable CT number linearity. Surface radiation dose was also measured to ensure output dose rate compliance with factory design and radiation safety standards (deviation $< 10\%$). Only after all acceptance steps were passed did we proceed to density curve reconstruction and dosimetric verification.

2.5 Reconstruction of CT Density Conversion Curves

Because CT numbers of materials had clearly drifted after tube replacement and system updates, new curves were required .

2.5.1 Eclipse System CT-RED Curve

The Eclipse treatment planning system uses the Anisotropic Analytic Algorithm (AAA) for dose calculation, which relies on accurate conversion of CT number to relative electron density (RED). Therefore, accurate CT-RED curves must be established. The CIRS-062M electron density phantom was used. This phantom contains 12 human tissue-equivalent materials and precisely associates CT numbers with electron densities of various equivalent tissues. Scans were performed with the chest scanning protocol (120 kV, 280 mAs, Filter Sharp(C), Enhancement 0.25). For each material, regions of interest (ROIs) were delineated in the TPS, and the mean CT number was recorded. Because CT numbers for the brain scanning protocol differed significantly from those of the chest protocol, a separate data set was acquired for the brain protocol. Each material was scanned multiple times at different positions (each clinical protocol was run twice on 17 different locations in the phantom) to provide comprehensive data for curve fitting. Using relative electron density (RED) as the ordinate and CT number as the abscissa, cubic spline interpolation curves were established. The curve for the chest/abdomen protocol was named Philips 16_2024, and the curve for the brain protocol was named Philips 16_2024_Brain. Some data points were smoothed according to Varian factory recommendations and departmental experience.

2.5.2 Tomo System CT-MD Curve

The CheesePhantom cylindrical phantom (diameter 30 cm, thickness 18 cm) was used with 8 gradient density material rods (mass density range 0.29–1.82 g/cm³). Scans were performed with the same scanning parameters, CT numbers were read in the Tomo planning system, and a CT-MD curve (named Philips 16_2024) was constructed using cubic spline interpolation with mass density as the ordinate.

2.6 Dosimetric Verification

2.6.1 Heterogeneous phantom planar dose verification (Eclipse)

The PTW T40037 heterogeneous phantom (with PMMA, tissue-equivalent, lung-equivalent, and bone-equivalent inserts) was used. A 20 cm × 20 cm square field plan was designed, and four energies (6X, 10X, 6FFF, 10FFF) were irradiated on the VitalBeam accelerator. Planar doses were measured with the Octavius 1500 detector, and 3D Gamma passing rates were analyzed at 3 mm/3% criteria. A total of 7 different material combination schemes were designed, each repeated 3 times.

2.6.2 Heterogeneous phantom point dose verification (Tomo)

Different density inserts were placed in the CheesePhantom, and Helical and Direct irradiation techniques (6FFF energy) were designed. Point doses at the center were measured with an A1SL ionization chamber (Standard Imaging, USA), and the relative deviation between measured and planned doses was calculated.

2.6.3 Real Patient Plan QA Verification

Nine Eclipse system patient plans and five Tomo system patient plans (covering head and neck, chest, abdomen, pelvis, spinal SBRT, liver SBRT) were randomly selected. The plans were transferred to the PTW Octavius 4D phantom (Eclipse) or ArcCheck phantom (Tomo), and doses were recalculated using the new density curves. The Gamma passing rates were compared with measured values, and also compared with the passing rates of the same plans before tube replacement.

2.7 Statistical Analysis

Measurement data were expressed as mean ± standard deviation. After Shapiro-Wilk test, the CT number data for the 8 Catphan504 materials were found to be normally distributed ($P > 0.05$). Paired t-tests were used to compare CT numbers before and after tube replacement, with Bonferroni correction for multiple comparisons (corrected significance threshold $\alpha = 0.05/8 = 0.00625$). For Gamma passing rates and other single comparisons, Wilcoxon signed-rank tests were used with a significance level of $P < 0.05$. SPSS 26.0 was used for all analyses.

2.8 Ethical Approval and Consent to Participate

This retrospective study used only routine equipment quality control datasets and did not involve individual patient data, biological samples, or clinical interventions. The study was reviewed and approved by the Institutional Review Board of The University of Hong Kong-Shenzhen Hospital (Approval/Waiver No. NO.2026060312002293). The requirement for informed consent was formally waived. All methods were performed in accordance with relevant guidelines and regulations, including the Declaration of Helsinki (as revised in 2013) and institutional quality assurance policies.

3 Results

3.1 Image quality after tube replacement

After tube replacement, all image quality indicators measured with the Catphan504 phantom under all clinical scanning protocols met the TG66 tolerance requirements. Taking the chest protocol as an example: spatial resolution reached 8 lp/cm (TG66 requirement ≥ 7 lp/cm), low-contrast CNR was 1.01 (≥ 0.64), horizontal slice thickness was 2.81 mm and vertical slice thickness 2.96 mm (target 3.0 ± 0.5 mm), and CT number uniformity was 3 HU (± 20 HU). Thus, tube replacement did not adversely affect conventional image quality.

3.2 CT number changes before and after tube replacement

CT numbers of 8 standard materials in the Catphan504 linearity module were measured before and after tube replacement using both the chest and brain protocols. After replacement, all materials showed systematic CT number drifts, and the drift direction and magnitude were closely correlated with effective atomic number (Z).

Table 2

Comparison of CT Values of Eight Materials Before and After Combined Intervention (Thoracic Protocol)

Materials	Effective Z	Pre-intervention CT Value (HU)	Post-intervention CT Value (HU)	Drift Value (HU)	95% CI	P Value
Air	7.64	-1000 ± 2	-967 ± 3	+ 33	(28,38)	< 0.001
Polystyrene	5.70	-47 ± 4	-26 ± 4	+ 21	(15,27)	0.002
Water Background	7.42	100 ± 1	104 ± 2	+ 4	(-2,10)	0.12
LDPE	5.31	-104 ± 3	-81 ± 3	+ 23	(17,29)	< 0.001
PMP	5.28	-196 ± 3	-170 ± 3	+ 26	(20,32)	< 0.001
Acrylic	6.52	115 ± 2	126 ± 2	+ 11	(5,17)	0.008
Delrin	6.85	366 ± 4	348 ± 4	-18	(5,17)	0.001
Teflon	8.43	1001 ± 10	938 ± 12	-63	(-73,-53)	< 0.001
Note: Paired t-test, n = 10 repeated scans. Bonferroni correction applied, significance threshold $\alpha = 0.00625$. Except for water background, all P values were < 0.00625. Relative change = (difference/absolute pre-replacement CT value)×100%, using - 1000 as baseline for air.						

As shown in Table 2, low-density, low-Z materials (air, polystyrene, LDPE, PMP) showed positive CT drifts (increase), while high-density, high-Z materials (Teflon, Delrin) showed negative drifts (decrease). The drift magnitude was significantly correlated with material Z (Pearson $r = -0.86$, $P < 0.001$): the lower the Z, the more positive the drift; the higher the Z, the more negative the drift. Teflon ($Z = 8.43$) showed the largest negative drift of - 63 HU, and air ($Z = 7.64$) showed a positive drift of + 33 HU.

3.3 New CT density conversion curves

Based on the CIRS-062M phantom's 12 tissue-equivalent materials and the CT number data in Table 3, CT-RED curves (standard curve Philips 16_2024 and brain-specific curve Philips 16_2024_Brain) for Eclipse and a CT-MD curve (Philips 16_2024) for Tomo were established. All curves were fitted using cubic spline interpolation, with coefficients of determination $R^2 > 0.99$ and root mean square errors (RMSE) < 0.015, indicating that the fitting accuracy meets clinical dose calculation requirements.

Table 3
RED and CT numbers of CIRS-062M materials (chest vs. brain protocol)

Material	RED	Chest protocol Mean(HU)	Brain protocol Brain(HU)
LUNG(IN)	0.190	-804.389	-809.1295
LUNG(EX)	0.489	-492.867	-494.38
ADIPOSE	0.949	-64.8825	-62.9235
BREAST	0.976	-36.695	-34.742
WATER	1.000	0	0
MUSCLE	1.043	45.348	56.0955
Liver	1.052	50.3895	57.141
BONE200	1.117	220.8675	195.652
BONE800	1.456	880.9815	851.064
BONE1250	1.695	1339.818	1315.392
BONECORE	1.976	1741.725	1705.238
TI	3.735	8376.7	7546.931
Note: RED = relative electron density. Data are mean values of multiple scans; smoothing was applied according to manufacturer recommendations and departmental experience.			

3.4 Dosimetric Verification Results

3.4.1 Heterogeneous phantom planar dose verification (Eclipse)

The 3 mm/3% Gamma passing rates for all energy levels were significantly higher than the 90% pass criterion recommended by AAPM TG119: 6X: $98.9 \pm 0.55\%$, 10X: $99.7 \pm 0.29\%$, 6FFF: $99.6 \pm 0.62\%$, 10FFF: $99.9 \pm 0.11\%$. No statistically significant differences were found among energies ($P > 0.05$). Figure 2 presents the boxplot of Gamma passing rates for the four energies.

3.4.2 Tomo System Point Dose Verification

Using the CheesePhantom and Helical/Direct irradiation techniques, point doses at the center of 8 different density inserts were measured. Under the new density curve, the relative deviations between planned and measured doses were within clinically acceptable ranges. Table 4 summarizes the point dose deviations for different plans.

Table 4
Relative Deviation of Tomo System Point Dose (New Curve vs Measured Value)

Plan Name	Irradiation Mode	Measured Dose (Gy)	Planned Dose (Gy)	Relative Deviation (%)
HN_Helical	Helical	2.0713	2.0760	-0.23
HN_Direct	Direct	2.0832	2.0764	+ 0.33
Cshape_Helical	Helical	2.1308	2.1020	+ 1.37
Cshape_Direct	Direct	2.1606	2.1332	+ 1.28
Prostate_Helical	Helical	3.0772	3.0422	+ 1.15
Prostate_Direct	Direct	3.0832	3.0356	+ 1.57
Multi_Helical	Helical	0.6428	0.6408	+ 0.32
Multi_Direct	Direct	0.6369	0.6348	+ 0.33
Mean ± Standard Deviation				0.76 ± 0.65

The relative deviations ranged from – 1.34% to + 1.57%, with a mean of 0.76%±0.65%. The confidence limit (mean + 1.96×SD) was 2.03%, below the 3% clinical tolerance. No significant difference was found between Helical and Direct techniques (P = 0.21).

3.4.3 Real patient plan QA

Nine Eclipse system patient plans and five Tomo system patient plans were randomly selected, and doses were recalculated using the new density curves and compared with measured Gamma passing rates. The results are presented in Tables 5 and 6.

Table 5
QA Passing Rates of Eclipse System Real Patient Plans (3 mm/3%)

Treatment Site	Energy	Pre-intervention Passing Rate (%)	Post-intervention Passing Rate (%)	Difference (%)
NPC	6X	100.0	99.9	-0.1
Pelvis (1)	6X	99.8	99.6	-0.2
Left Breast	6X	99.0	98.5	-0.5
Pelvis (2)	10X	98.6	99.9	+ 1.3
Right Lung	10X	99.6	99.2	-0.4
Spine SBRT	6FFF	99.8	99.7	-0.1
Liver SBRT	6FFF	99.9	100.0	+ 0.1
Right Lung SBRT	10FFF	99.7	99.8	+ 0.1
Mean ± SD	-	99.6 ± 0.5	99.6 ± 0.5	+ 0.03 ± 0.14

Wilcoxon signed-rank test: P = 0.68, no significant difference before and after intervention.

Table 6
QA Passing Rates of Tomo System Real Patient Plans (2 mm/3%)

Treatment Site	Irradiation Mode	Pre-intervention Passing Rate (%)	Post-intervention Passing Rate (%)	Difference (%)
Pelvis	Helical	99.3	100.0	+ 0.7
NPC	Helical	100.0	98.5	-1.5
Pelvis	Helical	98.3	98.5	+ 0.2
Knee Joint	Helical	98.4	99.0	+ 0.6
Throat	Helical	99.6	99.2	-0.4
Mean ± SD	-	99.1 ± 0.7	99.0 ± 0.6	-0.08 ± 0.90

Wilcoxon signed-rank test: P = 0.84, no significant difference before and after intervention.

P = 0.84, not significant.

All patient plan QA Gamma passing rates were greater than 98%, and there were no statistically significant differences before and after tube replacement, confirming that the newly reconstructed density conversion curves accurately maintained dose calculation accuracy. Figure 3 shows the scatter plot comparing patient plan QA passing rates before and after tube replacement.

3.5 Result Summary

In summary, conventional image quality indicators remained within TG66 tolerances and could not detect the systematic CT number drifts. Tube replacement and system updates caused significant non-uniform CT number drifts in 7 of the 8 Catphan504 materials (maximum – 63 HU for Teflon, + 33 HU for air), with drift direction strongly correlated with effective atomic number. The newly reconstructed density conversion curves based on 12 CIRS-062M materials achieved excellent fitting accuracy ($R^2 > 0.99$). Dosimetric verification showed that Gamma passing rates under the new curves far exceeded international guideline standards and showed no significant differences from pre-replacement values.

4 Discussion

The present study systematically evaluated the effects of CT tube replacement and subsequent system parameter updates on CT numbers and density conversion curves in radiotherapy treatment planning systems, and established a four-level quality control workflow consisting of acceptance testing, curve reconstruction, phantom dose verification, and patient-specific plan QA. The main findings were as follows: (1) After tube replacement and system updates, all conventional image quality indicators based on AAPM TG66 remained within tolerance limits, but clinically significant systematic CT number drifts were observed in 7 out of the 8 tissue-equivalent materials (excluding water background), with a maximum drift of – 63 HU; (2) these drifts could not be detected by routine image quality checks and could only be identified through multi-material phantom CT baseline re-measurement; (3) density conversion curves reconstructed for different scanning protocols (thorax/abdomen vs. brain) and multiple TPS platforms (Eclipse, Tomo) achieved excellent fitting accuracy ($R^2 > 0.99$), and rigorous phantom dose verification and real patient plan QA confirmed that the new curves ensured accurate dose calculation.

4.1 Deeper Physical Mechanism of CT Number Drift

CT number drift originated from changes in the X-ray energy spectrum after tube replacement and possible adjustments in reconstruction algorithms introduced by the software upgrade. Subtle differences between the new and old tubes in anode target surface, electron beam focusing, and inherent filtration led to a change in effective energy. In this study, low effective atomic number (Z) materials (air, polystyrene, LDPE, PMP) exhibited positive CT drifts (increase), whereas high-Z materials (Teflon, Delrin) exhibited negative drifts (decrease). The physical basis for this observation was beam hardening (reduction of low-energy photons) following tube replacement, which decreased the proportion of photoelectric effect. Low-Z materials interacted predominantly via Compton scattering; their mass attenuation coefficients changed little after spectral hardening, but the HU scale is normalized to water, so the CT numbers of low-Z materials increased relative to water after hardening. In contrast, the photoelectric effect dominated in high-Z materials, which was substantially suppressed after spectral hardening, leading to decreased CT numbers. Water (effective $Z = 7.42$) lies between these extremes, with photoelectric and Compton contributions roughly balanced; consequently, the water

background CT number changed by only + 4 HU, which was not statistically significant ($P = 0.12$). This pattern also explains a critical clinical shortcoming: routine quality control using only a water phantom uniformity test cannot detect spectral drifts, because water itself is insensitive to spectral changes, yet the CT numbers of key tissue-equivalent materials corresponding to bone, lung, and metal implants may have already shifted substantially.

4.2 Comparison with Existing Guidelines: From Image Quality to Dosimetric Closed-Loop

Current international quality control guidelines (AAPM TG66, IAEA 31, IPEM 91) only require routine image quality re-testing after major CT hardware maintenance (spatial resolution, slice thickness, water phantom CT uniformity, etc.) and do not mandate updating density conversion curves. Although IPEM Report 81 suggests that conversion curves should be re-established when CT number changes exceed 10–20 HU, this threshold is empirical and lacks standardized operational procedures. The data from the present study showed that even when all TG66 indicators passed, the CT number change for Teflon reached as high as 63 HU, far exceeding the IPEM threshold. Therefore, reliance solely on traditional image quality control has a serious blind spot.

The four-level quality control workflow proposed in this study—(1) acceptance testing (dynamic balance, filament calibration, tube conditioning, position/collimator/focus calibration, air scan) → (2) multi-material CT baseline re-measurement → (3) density curve reconstruction (differentiating scanning protocols and TPS) → (4) dosimetric verification (phantom planar dose + patient-specific plan QA)—supplements existing guidelines with a ready-to-implement standardized protocol. A comparison with current guidelines is presented in Table 7.

Table 7

Comparison of quality control requirements after major CT repairs among different guidelines/studies

Guideline / Study	Coverage	Mandatory Curve Reconstruction	Dosimetric Verification Included
AAPM TG66	Image quality (uniformity, resolution, etc.)	No	No
IAEA 31	Image quality and radiation dose	No	No
IPEM 91	Same as above	Suggested when HU change > 10–20 HU, but no standardized workflow	No
Present study (four-level workflow)	Image quality + CT baseline + curve reconstruction + phantom/patient QA	Yes (mandatory)	Yes (Gamma validation)

4.3 Quantitative Clinical Risk Assessment and Threshold Recommendations

The most pronounced drift in this study was observed for Teflon (high-Z material), reaching – 63 HU. According to the CIRS phantom calibration data, the relative electron density (RED) of Teflon is approximately 1.65 (between BONE1250 RED = 1.695 and BONECORE RED = 1.976); a change of 63 HU corresponds to a RED change of about 0.04. In radiotherapy dose calculation, a RED change of 0.04 in the vicinity of bone (RED $\approx$ 1.3–1.8) or metal implants can induce a dose calculation error of 1%–3%, which is sufficient to affect target coverage and organ-at-risk doses in SBRT/SRS. For example, in spinal SBRT, the dose gradient at the bone-soft tissue interface can reach 10%/mm; a 1% error translates into a 0.1 mm shift in isodose lines, which is clinically significant for a 2–3 mm spinal cord planning organ-at-risk volume.

Based on the present data and the literature, we propose the following reference thresholds: if the CT number change of any high-Z material (e.g., Teflon, Delrin, or bone-equivalent material) exceeds 20 HU, or that of any low-Z material (e.g., lung or fat-equivalent material) exceeds 15 HU, then density conversion curves should be reconstructed for all clinical scanning protocols. Individual centers may adjust these thresholds according to their specific equipment characteristics and clinical precision requirements.

4.4 Standardized Clinical Recommendations

Based on the above physical mechanisms, guideline comparison, and quantitative risk assessment, we propose the following actionable standardized clinical quality control workflow, which should be enforced after CT tube replacement or major software upgrades:

Air calibration must be performed first: immediately after replacement, an air scan should be executed to establish new detector offset and gain baselines, targeting an air CT number of -1000 ± 5 HU. Multi-material CT baseline measurement is mandatory: a CIRS 062M or equivalent electron density phantom should be used to measure CT numbers of at least eight tissue-equivalent materials (including air, water, low-Z, and high-Z materials) and compare them with the pre-replacement baseline. Curve reconstruction trigger thresholds should be set: if the CT number change of any high-Z material (e.g., Teflon, Delrin, or bone-equivalent material) exceeds 20 HU, or that of any low-Z material (e.g., lung or fat-equivalent material) exceeds 15 HU, then density conversion curves must be reconstructed for all clinical scanning protocols (thorax/abdomen, brain, etc.). Dosimetric verification is required after reconstruction: heterogeneous phantom planar dose verification (Gamma passing rate $\geq 90\%$ at 3 mm/3%) and at least three representative patient plan QAs (covering different anatomical sites and energies) must confirm dose calculation accuracy before clinical use. Furthermore, the hierarchical diagnosis logic proposed in Section 2.1.2 (intermittent sparking $\rightarrow$ high-voltage plug; persistent high-voltage errors $\rightarrow$ high-voltage package; residual image/conditioning problems $\rightarrow$ tube itself) should be applied in routine fault troubleshooting to improve maintenance efficiency and extend equipment life.

4.5 Innovations and limitations

Innovations: (1) For the first time, progressive tube fault diagnosis and hierarchical troubleshooting were integrated with dosimetric verification in radiotherapy treatment planning systems, revealing the

complete causal chain from hardware failure to dose deviation; (2) CT number drift patterns for eight different Z-materials after the combined intervention were quantified, and a strong correlation between drift direction/magnitude and Z was demonstrated; (3) a four-level quality control workflow comprising acceptance testing, density curve reconstruction (differentiating scanning protocols and TPS), phantom dose verification, and patient-specific plan QA was established, with reference thresholds proposed, supplementing the deficiencies of existing international guidelines.

Limitations: (1) The independent effects of tube replacement and software upgrade could not be separated; the conclusions reflect a combined intervention effect, and strictly controlled studies are needed in the future; (2) only a single CT model and two TPS systems were involved; extrapolation to other equipment requires caution; (3) long-term stability was not assessed within the scope of this study, and longitudinal follow-up is recommended; (4) the specific dose deviation that would result from using the old density curve was not directly quantified (the 1%–3% error range was estimated from the literature); a future controlled experiment could directly measure this.

4.6 Clinical Implications

The core implication of this study is that passing routine image quality acceptance does not guarantee dose calculation accuracy. As the “language” connecting imaging and dosimetry, CT numbers have hidden drifts that can only be captured through multi-material phantoms and dosimetric closed-loop validation. Radiotherapy departments should incorporate “reconstruction of density curves after tube replacement or major software upgrades” into their routine quality control workflow and establish standard operating procedures. Only by forming a closed loop of hardware acceptance, image quality control, curve reconstruction, and dose verification can the safety and efficacy of precision radiotherapy be truly ensured.

5 Conclusion

Replacement of the CT X-ray tube and subsequent system parameter updates cause systematic CT number shifts in different tissue-equivalent materials, with high-density materials showing the most significant shifts. Routine TG66 image quality testing is insufficient to detect such changes; re-measurement of CT number baselines using the 8-material Catphan504 module and reconstruction of new density conversion curves using the 12-material CIRS-062M phantom are mandatory. Post-replacement acceptance testing must include a complete stepwise workflow from mechanical calibration to electrical activation to image quality verification. After rigorous dosimetric validation, the new curves ensure that dose calculation accuracy meets clinical requirements. It is recommended that “reconstruction of density curves after tube replacement or major software upgrades” be included in the routine quality control workflow of radiotherapy departments, and that the hierarchical diagnosis strategy be applied to fault troubleshooting of similar CT equipment.

Declarations

Ethical Statement and Conflicts of Interest

Ethical Statement

All analyses were performed retrospectively based on routine equipment quality control datasets without individual patient enrolment or clinical intervention; ethical approval was waived in accordance with the institutional review board regulations of the participating hospital.

Conflict of Interest

No relevant financial or commercial conflicts of interest were declared by all contributing authors.

Author Contributions

CXC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing -original draft, Writing - review & editing. YYS: Data curation, Software, Validation, Writing -review & editing. GJX: Investigation, Visualization, Writing - review & editing. JWY: Conceptualization, Project administration, Supervision, Writing -review & editing. YTY: Formal analysis, Software, Validation, Writing - review & editing. All authors contributed to the article and approved the submitted version.

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The author(s) declared that generative AI was not used in the creation of this manuscript.

Conflict of Interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Data Availability Statement

The authors declare that no financial support was received for this work or its publication. The datasets analysed in this study were derived from routine quality control procedures of the Radiotherapy Center at The University of Hong Kong – Shenzhen Hospital. These institutional data are not publicly available due

to ethical and patient privacy restrictions, and were used only within the scope of this study with institutional approval. Requests for access to these institutional data should be directed to Chunxiang Chen (chencx216@163.com) and are subject to approval by the relevant ethics committee and institutional data-sharing requirements.

Ethics Statement

This retrospective study used only routine equipment quality control datasets; no individual patient data, biological samples, or clinical interventions were involved. Therefore, neither informed consent nor formal ethics committee approval was required according to national regulations (Guidelines for Ethical Review of Biomedical Research Involving Human Subjects, National Health Commission of the People's Republic of China). The need for informed consent and ethics approval was formally waived by the Institutional Review Board of The University of Hong Kong – Shenzhen Hospital (waiver approval No. NO.2026060312002293). All methods were performed in accordance with relevant guidelines and regulations, including the Declaration of Helsinki (as revised in 2013) and the institutional quality assurance policies.

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Figures

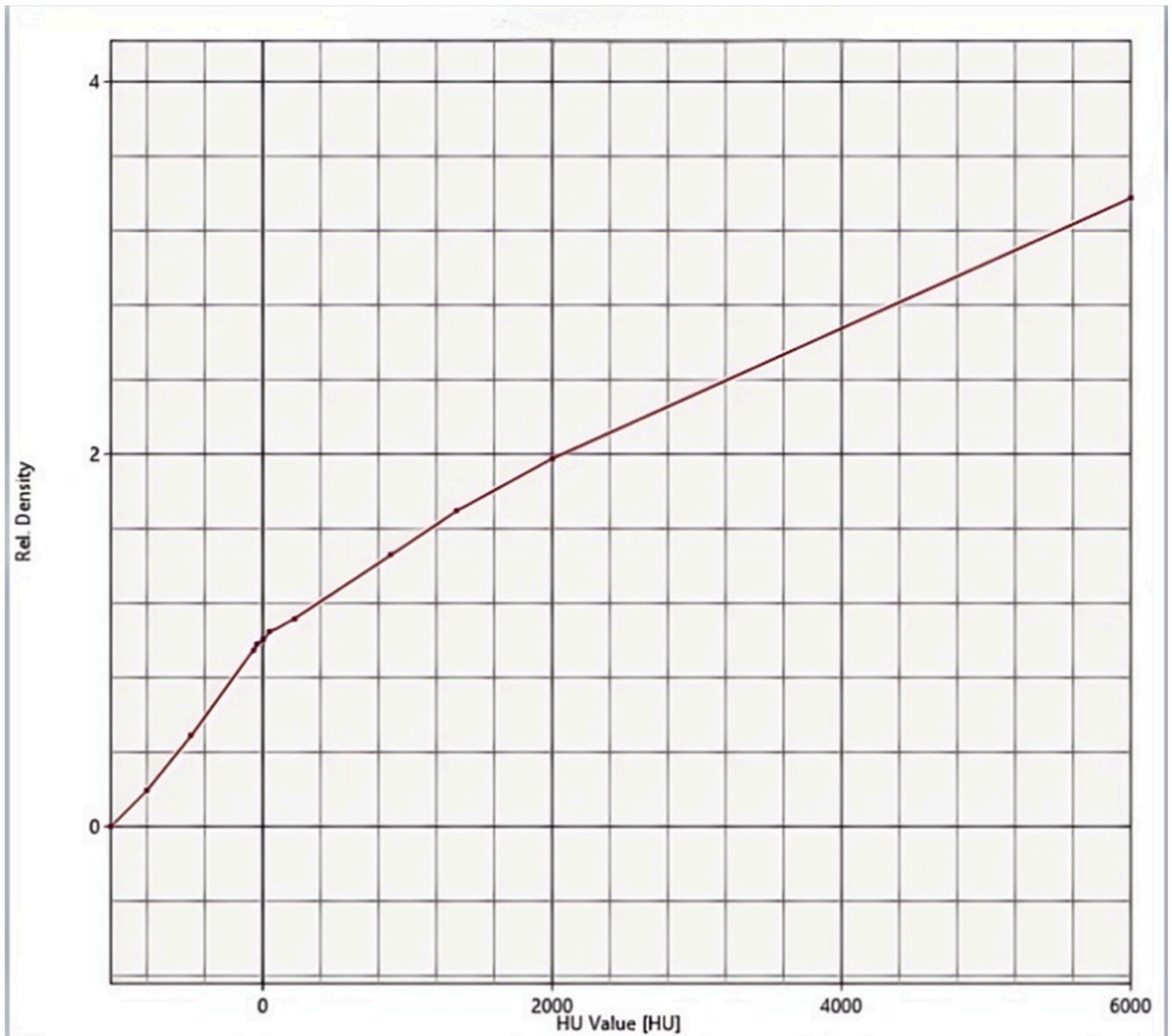


Figure 1

shows the CT-RED curve for the chest protocol (Philips 16_2024) with cubic spline interpolation.

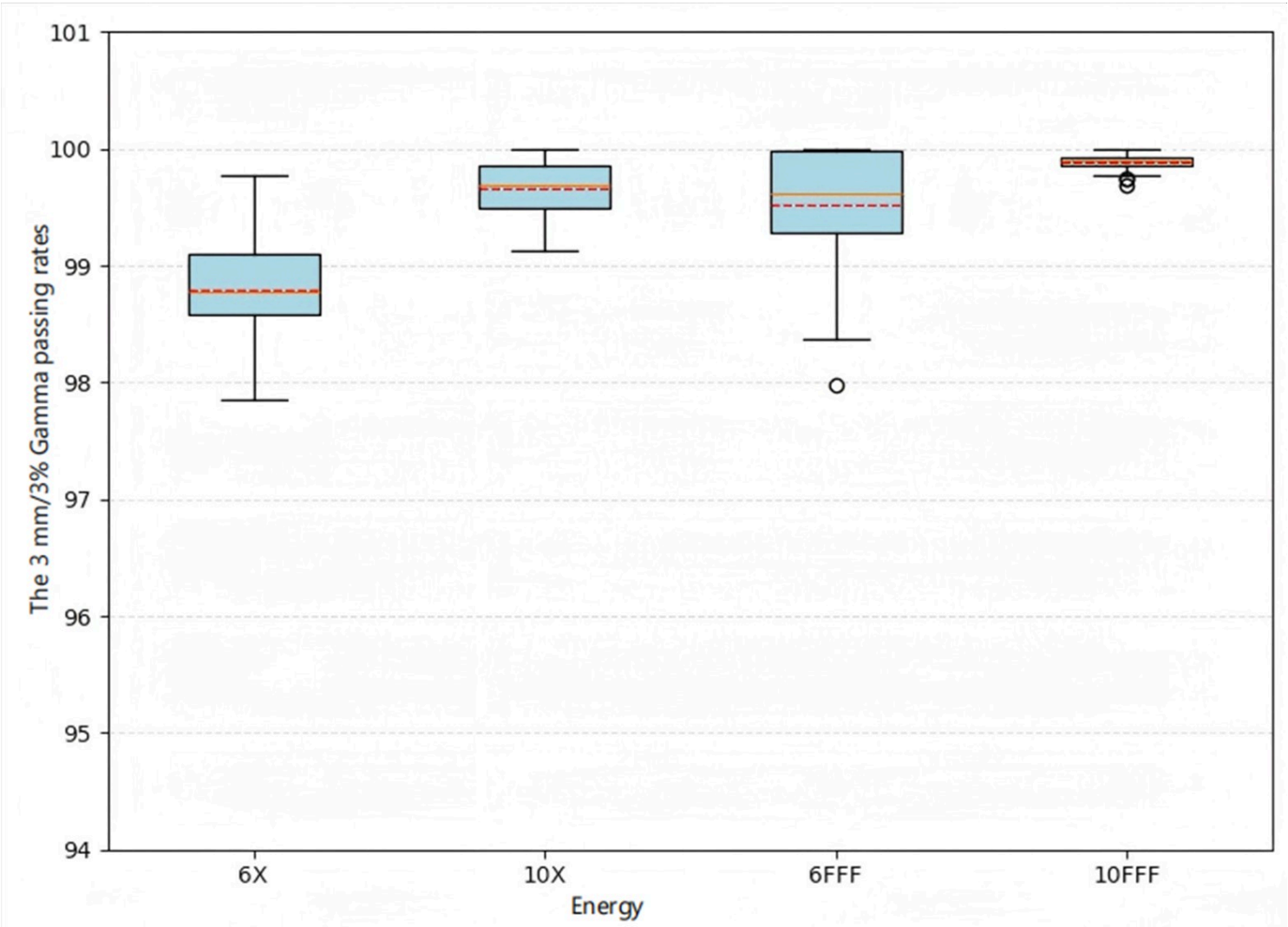


Figure 2

presents the boxplot of Gamma passing rates for the four energies.

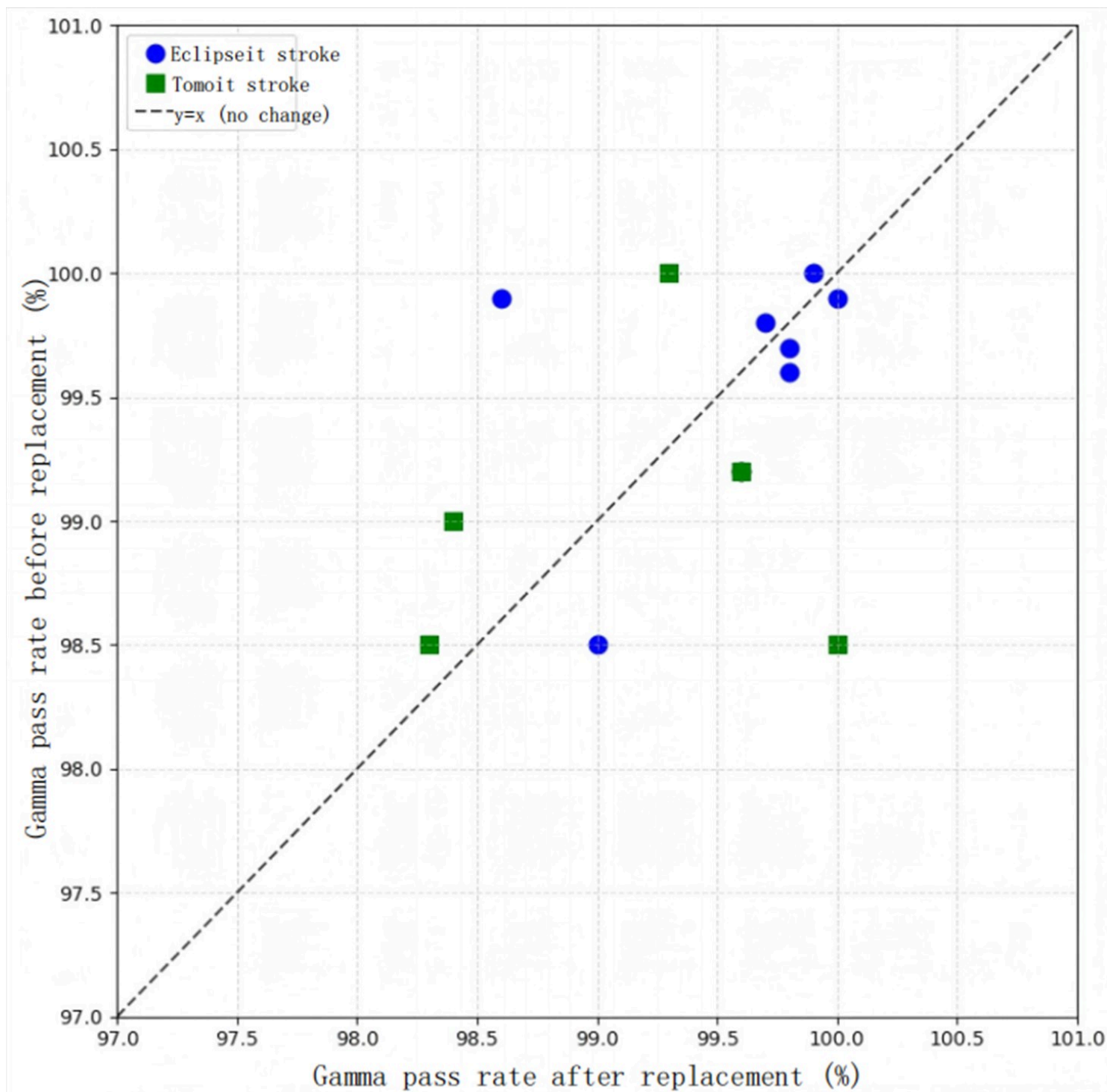


Figure 3

shows the scatter plot comparing patient plan QA passing rates before and after tube replacement.