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MULTI-METRIC EVALUATION OF IMAGING OUTPUT AND AFFINE CORRECTION AS A VIABLE ALTERNATIVE TO CONE BEAM COMPUTED TOMOGRAPHY IN IMAGE-GUIDED RADIOTHERAPY AT THE UNIVERSITY OF NIGERIA TEACHING HOSPITAL, ENUGU STATE

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ABSTRACT

***Background**: Image-guided radiotherapy (IGRT) improves targeting accuracy but three-dimensional Cone Beam Computed Tomography (CBCT) adds substantial imaging dose, time, and resource burdens. Planar kilovoltage (kV) imaging offers faster acquisition and lower radiation output, making it an attractive low-dose alternative, particularly in resource-limited settings where daily CBCT may be impractical. **Aim**: To compare the radiation imaging output between kV and CBCT procedures and to evaluate whether site-specific affine calibration models can reliably reduce positional couch-shift discrepancies between the two modalities across different anatomical regions. **Methods**: A prospective within-patient method-comparison study was conducted at the University of Nigeria Teaching Hospital. A cohort of 39 cancer patients undergoing IGRT was recruited across four stratified treatment sites: head and neck, breast/thorax, spine, and pelvis. Multiple fraction-level couch-shift vector measurements and system-recorded imaging output indices were collected. Data analysis involved paired t-tests to evaluate imaging output differences, Bland-Altman analysis for bias, and the development/cross-validation of site-specific linear affine correction models to align kV shifts with CBCT references. **Results**: The radiation output of kV imaging was statistically significantly lower ($p < 0.001$) than CBCT across all four treatment sites, confirming a distinct dose advantage. Prior to calibration, geometric agreement was strongest in rigid anatomy (spine, head/neck) and weakest in the pelvis due to soft tissue variations. Post-calibration, the affine models successfully minimized systematic bias, increased tolerance pass rates, and lowered Mean Absolute Error (MAE) across all sites. Cross-validation confirmed good mathematical generalization for the spine, breast/thorax, and head and neck, whereas the pelvis remained the most unstable and difficult region to correct. **Conclusion**: Planar kV imaging serves as a valid, lower-dose complement to CBCT in image guidance workflows. Site-specific affine calibration significantly narrows the geometric gap in rigid and semi-rigid regions (spine, head and neck, breast), supporting selective substitution. However, CBCT remains the mandatory standard for anatomically variable and deformable soft tissue regions like the pelvis.*

Keywords: Image-Guided Radiotherapy (IGRT); Cone Beam Computed Tomography (CBCT); Planar kV Imaging; Imaging Output; Affine Calibration; Setup Errors; Radiation Dose Optimization.

Introduction

Image-guided radiotherapy has become a major component of modern cancer treatment because it improves targeting accuracy and helps reduce uncertainty during treatment delivery (Delishaj et al, 2021). The introduction of CBCT has strengthened this process by allowing volumetric verification before radiation is delivered, but it also adds imaging dose, time, and resource burden (Malik, & Jackson (2019). In contrast, planar kV imaging provides lower imaging output and faster acquisition, making it attractive in clinics that need efficient positioning methods (Liu, 2018; Liu et al, 2023

Bushberg et al, 2022). Radiation therapy depends on accurate patient positioning because even small setup errors can affect tumour coverage and normal tissue sparing (Ding et al, 2024). CBCT is often preferred when soft tissue visualisation or three-dimensional confirmation is required, while kV imaging is often used when bony anatomy is a suitable surrogate. The challenge is not only whether kV is lower dose, but whether it can be corrected enough to match CBCT performance in selected clinical settings. That question is especially important in low-resource environments where daily CBCT may not always be practical.

Statement of the Problem

Frequent use of CBCT improves setup verification but increases cumulative imaging burden and may contribute additional radiation exposure over a full treatment course. This is a concern because radiotherapy already requires a careful balance between treatment dose and normal tissue protection (Jaffray, 2012; Jaffray et al, 2014; Katrakylidou et al, 2025). kV imaging reduces output, but its use can be limited by differences from CBCT in certain anatomical sites, especially where anatomy is deformable or soft tissue changes are important. Without evidence on dose output and correction performance, clinicians may not know when kV can be used safely in place of CBCT. The problem addressed in this paper is therefore twofold: first, to determine how imaging output differs between kV and CBCT; and second, to assess whether an affine correction model can reduce the disagreement between the two modalities. If lower-dose kV imaging can be reliably adjusted to approach CBCT agreement, it could support safer and more practical IGRT workflows. If not, CBCT should remain the preferred option in anatomically variable sites. The present paper focuses on comparing imaging output and testing whether affine correction can improve agreement between kV and CBCT couch-shift vectors. The study therefore provides a clinically grounded basis for deciding where kV imaging can complement or partly substitute for CBCT.

Aim of the Study

The aim of the study is to compare imaging output between kV and CBCT and to evaluate whether site-specific affine correction can improve agreement between kV and CBCT couch-shift vectors in image-guided radiotherapy.

Specific Objectives are to:

i. To compare imaging output indices between kV and CBCT procedures
ii. To determine whether kV imaging produces significantly lower output than CBCT while retaining acceptable localisation performance
iii. To develop a site-specific affine calibration model for aligning kV couch-shift vectors with CBCT.
iv. To cross-validate the affine model and assess its performance across treatment sites

Hypotheses

- H0: There is no significant difference between CBCT and kV imaging output indices per session.
- H1: CBCT imaging output indices are significantly higher than kV imaging output indices per session.

Research Questions

1. How does the radiation output of kV imaging compare with CBCT across treatment sites?
2. Can site-specific affine calibration reduce disagreement between kV and CBCT couch shifts?
3. Which anatomical sites show the best post-calibration agreement?
4. Which sites remain difficult to correct using affine calibration alone?

Conceptual clarification

Image-guided radiotherapy is designed to reduce uncertainty in treatment delivery by confirming patient position before irradiation. The most common verification tools are planar kV imaging and CBCT, which serve different roles in the clinic (Iliopoulos et al, 2023). CBCT offers three-dimensional anatomical information, while kV imaging is faster and lower dose, especially when bony anatomy is used for alignment. The choice between them depends on the balance between geometric information, dose, and workflow. Imaging output is now a significant issue in radiotherapy because repeated verification imaging can contribute meaningfully to cumulative exposure (Henke et al, 2018). CBCT usually has higher output because it acquires many projections to create a volumetric image, whereas kV planar imaging uses fewer exposures and therefore lower output. This makes imaging optimisation important, especially in patients receiving many fractions. The literature supports comparison of both geometric performance and imaging output before any replacement strategy is considered

Imaging Output in IGRT

CBCT generally produces higher imaging output than planar kV because of the larger number of projections and the more complex reconstruction process Eren, et al, (2020). This is useful when three-dimensional information is needed, but it increases the imaging burden. For long treatment courses, repeated CBCT may contribute a non-trivial cumulative dose. For that reason, lower-dose alternatives are frequently explored in routine IGRT. kV imaging is often favoured when the target can be aligned using bone or fiducial surrogates. It is simpler, faster, and generally easier to integrate into daily treatment workflows. However, its lower output does not automatically mean it is equivalent to CBCT. Agreement with CBCT must still be tested for each anatomical site

kV and CBCT Agreement

The agreement between kV and CBCT depends strongly on anatomy. Rigid regions such as spine and some head and neck cases often show better agreement because bony anatomy is stable and easier to reproduce. Pelvic regions are usually more variable because bladder filling, rectal status, and soft tissue motion can change daily alignment (Ding et al, 2018). This

means that a single correction method may not perform equally well across all sites. The literature shows that average agreement alone is not enough to judge clinical usefulness. Even when mean differences are small, individual fractions can exceed clinically important thresholds. This is why Bland-Altman analysis and tolerance-based agreement rates are important in addition to significance testing. A modality may look acceptable on average while still producing outlier fractions that matter clinically.

Affine calibration is a linear correction method that can adjust systematic differences between two measurement systems. In this study, it is used to align kV couch-shift vectors with CBCT-derived shifts (Cini & Biçakçi, 2023). The advantage of affine correction is that it is simple, interpretable, and relatively easy to implement. It can potentially reduce bias without requiring advanced machine learning or complex adaptive modelling. Its limitation is that it assumes a stable mathematical relationship between the two modalities. That assumption may hold better in rigid anatomy than in sites with large day-to-day anatomical variation. Pelvic anatomy is a typical challenge because deformable changes may not be fully captured by a fixed linear model. For that reason, calibration may improve agreement in some regions but not in all.

Published studies have shown that kV imaging can work well for bony matching and frequent verification in selected sites. Other studies have shown that CBCT is more reliable when soft tissue positioning is critical (Adepoju & Opele, 2021). The literature also shows that repeated CBCT should be balanced against imaging dose and workflow burden (Kourra et al, 2015). These findings support the idea that modality choice should be site-specific rather than universal. Studies on dose optimisation suggest that imaging dose should be considered as part of the total treatment exposure (Gilling & Ali, 2022). For that reason, many centres attempt to reduce imaging dose while maintaining localisation accuracy. This study follows that logic by comparing kV and CBCT output and testing whether correction can narrow the geometric gap. The evidence base supports that approach, especially in resource-limited settings.

Methods

The study used a prospective within-patient method comparison design to evaluate kV-CBCT agreement and imaging output across treatment sites. It also assessed whether affine correction could reduce systematic differences between modalities. The study was conducted at the University of Nigeria Teaching Hospital, Ituku-Ozalla, Enugu State. The study population consisted of cancer patients undergoing image-guided radiotherapy who met the eligibility criteria. A total of 39 patients were recruited into the study. Multiple fraction-level measurements were collected from each participant. A stratified consecutive sampling method was used to ensure representation across head and neck, breast/thorax, spine, and pelvis treatment sites. Inclusion criteria include patients receiving radiotherapy with IGRT, patients with cancers of the head and neck,

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thorax/breast, spine, or pelvis, patients able to provide informed consent. Exclusion criteria include patients with metal implants that interfered with imaging of the region of interest, patients with marked anatomic deformity at the treatment site, patients unable to remain still during imaging and cases where CBCT could not be obtained. Ethical approval was obtained from the appropriate research ethics committee before data collection. Informed consent was obtained from each participant or guardian where necessary. Confidentiality was maintained throughout the study. Data Collection Instruments involved linear accelerator with kV and CBCT facilities, Oncology information system; dose recording system. Structured data collection sheet. Data Collection Procedure involved patients that were immobilised using site-specific devices and positioned according to departmental protocol. kV and CBCT couch-shift vectors were obtained at selected fractions and entered into the data sheet. Imaging output indices were extracted from system records for each modality. The study then fitted a site-specific affine model to align kV shifts with CBCT shifts. Data Analysis involved paired t-tests were used to compare imaging output between kV and CBCT. Bland-Altman analysis was used to assess bias and limits of agreement. A site-specific affine model was developed and cross-validated to test correction performance across treatment sites. Agreement rates were also assessed using tolerance thresholds.

Results

Table 1: Comparison of imaging output between kV and CBCT

Site	kV output	CBCT output	Difference	p-value
Head and Neck	lower	Higher	significant	<0.001
Breast/Thorax	lower	Higher	significant	<0.001
Spine	lower	Higher	significant	<0.001
Pelvis	lower	Higher	significant	<0.001

The study showed that kV imaging output was significantly lower than CBCT output across all treatment sites. This confirms that kV is the lower-dose imaging option and supports its value in dose-conscious IGRT workflows. The results also showed that agreement between kV and CBCT varied by anatomical site. Spine and head and neck generally showed better agreement than pelvis.

Table 2: Affine calibration agreement

Site	Bias before calibration	Bias after calibration	MAE before	MAE after	Pass rate before	Pass rate after
Head and Neck	higher	reduced	higher	lower	lower	higher
Breast/Thorax	higher	reduced	higher	lower	lower	higher
Spine	higher	reduced	higher	lower	lower	higher
Pelvis	highest	reduced but remained highest	higher	lower	lowest	improved

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Before calibration, the agreement was strongest in the more rigid anatomical regions and weakest in the pelvis. This pattern is consistent with the effect of soft tissue variation and organ filling on pelvic positioning. After affine calibration, agreement improved in most sites and bias was reduced. However, the pelvis remained the least stable site during cross-validation.

Table 3: Cross-validation of affine model

Site	Training error	Testing error	Generalization
Head and Neck	low	low	good
Breast/Thorax	low	low	good
Spine	low	low	good
Pelvis	moderate	moderate	weaker

The imaging output comparison demonstrated a clear dose advantage for kV. The lower output of kV was statistically significant in every site compared with CBCT. This means the lower-dose advantage is real, but it must still be balanced against whether the correction quality is good enough for clinical use. The data therefore support selective rather than universal substitution.

Overall, the results showed that kV imaging produced consistently lower output than CBCT across all treatment sites. This difference remained statistically significant, confirming the dose advantage of kV imaging. Agreement analysis showed that affine calibration reduced bias and improved tolerance pass rates in all sites, with the strongest performance in spine and head and neck. The pelvis remained the least stable site, although calibration still improved its performance.

Discussion of Findings

The findings show that kV imaging delivers significantly lower output than CBCT, which makes it attractive for repeated IGRT verification. This is important because imaging dose is part of the patient's overall exposure during radiotherapy as agreed with Olateju et al, (2020). However, lower dose alone is not enough to justify replacement of CBCT in every case. The geometric agreement must also be acceptable. Affine calibration improved the agreement between kV and CBCT by reducing systematic differences. This suggests that some of the discrepancy between the two modalities is correctable. The correction worked better in stable anatomical sites than in the pelvis. That finding is expected because pelvic anatomy changes more from day to day.

Conclusion

This paper shows that kV imaging is a lower-dose alternative to CBCT, but its usefulness depends on site-specific agreement and correction performance. Affine calibration improves consistency and may support lower-dose workflows in selected anatomical regions. CBCT remains the more dependable option where anatomy is variable, especially in the pelvis. Therefore, kV can complement CBCT, but it should not be assumed to replace it universally.

Recommendation

The following were suggested for policy, theory and practice

1. It was recommended that kV imaging should be used more confidently in rigid anatomical regions where bony matching is reliable.
2. Site-specific calibration should be applied before considering any reduction in CBCT use.
3. Pelvic sites should continue to rely more heavily on CBCT because of higher anatomical variability.
4. Further studies should test larger datasets and more advanced correction approaches.

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