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Original article

Quality Control (Field Congruence and Beam Perpendicularity Tests) For Diagnostic X-Ray Machines in Misurata City

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Abstract
Diagnostic radiology is a cornerstone of modern clinical medicine; however, it constitutes a primary artificial source of ionising radiation exposure to the general population. Maintaining high diagnostic image quality while adhering to radiation protection standards relies fundamentally on periodic quality control (QC) testing of radiographic systems. This study evaluates the operational performance of conventional diagnostic X-ray machines across selected public healthcare facilities in Misurata city by assessing light-to-X-ray field congruence (collimation alignment) and central ray beam perpendicularity. Six diagnostic X-ray units distributed across four healthcare centres were tested using standardized commercial beam and collimator alignment tools at a source-to-image receptor distance (SID) of 100 cm. Compliance was benchmarked against international regulatory tolerances: ≤ 2% of the SID for single-axis field congruence, < 4% for combined orthogonal axes, and < 3° for central ray angular deviation. All six evaluated units achieved a 100% pass rate across both tests. Single-axis displacements ranged from -1.50 cm to +0.50 cm (within the 2.0 cm limit), while combined orthogonal deviations ranged from 1.08 cm to 3.35 cm (within the 4.0 cm limit). Furthermore, central ray angular deviations remained within acceptable thresholds (0.5° to < 3°). These findings confirm robust mechanical calibration and high geometric accuracy across the surveyed units, directly supporting diagnostic reliability and upholding the ALARA (As Low as Reasonably Achievable) principle by minimizing patient radiation doses from unnecessary retakes and improper collimation.
Keywords. Quality Control, Field Congruence, Beam Perpendicularity, Diagnostic X-Ray, Radiation Protection.

Introduction

Diagnostic X-ray imaging is an indispensable modality in contemporary clinical practice, providing a rapid, non-invasive, and cost-effective means to guide medical and surgical decision-making [1]. High radiographic image quality is essential for accurate diagnosis and effective patient management, as suboptimal images frequently necessitate repeat examinations that increase healthcare costs and subject patients to avoidable ionising radiation [2]. Radiographic image quality is governed by the interplay of spatial resolution, subject contrast, and image noise, alongside precise geometric calibration of the X-ray tube and collimator assembly [2, 3]. To achieve and sustain optimal imaging performance, comprehensive quality assurance (QA) and quality control (QC) programs —executed through periodic calibration and preventive maintenance by medical physicists, biomedical engineers, and radiographers— are critical for balancing image quality against patient radiation dose [4].

Among the geometric parameters affecting radiographic accuracy, central ray perpendicularity and light-to-X-ray field congruence are particularly vital. Any angular misalignment of the central X-ray beam introduces unequal geometric magnification and spatial distortion, which can obscure anatomical landmarks and impair diagnostic interpretation [5]. Likewise, discrepancies between the visual light field and the actual X-ray beam can cause anatomical cutoff—leading to repeat exposures—or result in unnecessary irradiation of tissues outside the region of interest, thereby increasing patient dose and degrading image contrast through excess scatter radiation [6].

Despite the clinical and radiological significance of these tests, periodic QC evaluations often receive insufficient attention in routine clinical workflows, resulting in a lack of documented baseline performance data for public diagnostic facilities. Previous international investigations have demonstrated that systematic testing using specialised collimator and beam alignment tools effectively identifies mechanical drift and establishes critical safety benchmarks [7–10]. Accordingly, this study was conducted to evaluate light-to-X-ray field congruence and central ray beam perpendicularity across six diagnostic X-ray machines in four public healthcare centres in Misurata city, comparing the empirical results against international tolerance limits established by the National Centre for Devices and Radiological Health / Food and Drug Administration (NCDRH/FDA) and the National Council on Radiation Protection and Measurements (NCRP Report No. 99).

Methods

Study Design and Sample

This empirical cross-sectional study was conducted across four public healthcare facilities in Misurata city, Libya, over three months from February to April 2026. A total of six conventional diagnostic X-ray units were comprehensively evaluated. Three of the participating centres operated a single X-ray unit each (designated as units A, B, and C), whereas the fourth facility housed three operational units (designated as D1, D2, and D3). Comprehensive equipment metadata, including manufacturer specifications, model types, and commissioning dates, were documented to investigate potential correlations between equipment operational age and mechanical performance.

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Testing Equipment and Experimental Setup

To evaluate the geometric alignment between the optical collimator assembly and the primary X-ray focal spot [11, 12], standardised commercial Beam and Collimator Alignment QC Test Tools were employed in strict adherence to international quality control protocols [13–15]. The collimator test assembly comprised a rectangular metallic plate (20 × 25 cm) etched with calibrated rectangular frames and reference markers to measure edge displacement, paired with a specialised glass cylinder (16 cm height, 7 cm diameter) containing two 1.6 mm radiopaque steel attenuator balls positioned coaxially at its upper and lower extremities. Initially, the radiographic examination table was levelled using a spirit level, and the image receptor (cassette) was precisely centred on the tabletop. The X-ray tube assembly was then positioned perpendicular to the table surface, with the source-to-image receptor distance (SID) set strictly to 100 cm. Subsequently, the collimator test plate was centred over the image receptor with its reference marker oriented toward the cathode side to maintain consistent spatial orientation, and the beam alignment cylinder was placed directly at the geometric centre of the plate (Figure 1). The collimator shutter blades were adjusted until the projected light field coincided precisely with the etched rectangular boundaries on the test plate. Finally, radiographic exposures were acquired using standardised baseline parameters of 60 kVp and 2 mAs, followed by image processing and quantitative manual measurement of field edge displacements.

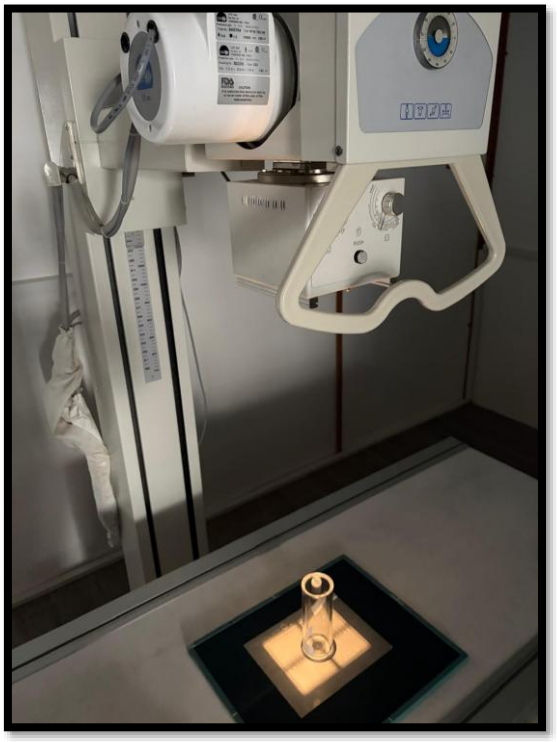


Figure 1. Experimental Setup showing the beam alignment test tool positioned on the radiographic table at SID = 100 cm

Data analysis and evaluation criteria

Displacements between the visual light field edges and the exposed X-ray field edges were measured manually using a millimetre-graduated ruler (with an associated measurement uncertainty of ± 0.05 cm, corresponding to half the smallest scale division of 1 mm) along the horizontal (X1: right edge, X2: left edge) and vertical (Y1: upper edge, Y2: lower edge) axes, where positive (+) values denote an X-ray field dimension exceeding the light field and negative (−) values indicate an X-ray field smaller than the light field. Equipment compliance was evaluated against two established international benchmarks [15, 16]:

Single-Axis Tolerance (2% Rule)

Misalignment along any individual edge or axis must not exceed 2% of the operational SID (2.0 cm at SID = 100 cm).

Combined-Axis Tolerance (4% Rule)

The sum of absolute misalignments across orthogonal axes (ΔX + ΔY = |X1| + |X2| + |Y1| + |Y2|) must remain below 4% of the SID (4.0 cm at SID = 100 cm).

For central ray perpendicularity, the projected shadow positions of the upper and lower steel attenuator balls were evaluated relative to concentric reference rings on the test cylinder [17]. Exact coaxial superimposition signified optimal alignment (0°), contact with the inner ring boundary indicated an acceptable minor deviation (1.5°), and shadow displacement reaching or exceeding the outer ring boundary (≥3°) denoted a critical misalignment failure requiring corrective calibration.

Results

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Light-to-X-Ray Field Congruence

(Table 1) details the individual edge displacements (X1, X2, Y1, Y2) and compliance status evaluated against the 2% single-axis tolerance limit across all six diagnostic X-ray units. Individual edge displacements ranged from −1.50 cm to +0.50 cm. Notably, the majority of non-zero edge displacements (14 out of 22) exhibited negative values, indicating that the actual X-ray radiation field was slightly smaller than the projected light field. Although unit D3 demonstrated the largest single-edge displacement along the X1 axis (−1.50 cm; Figure 2b), all measured parameters across every facility remained strictly within the permissible ≤ 2.0 cm threshold.

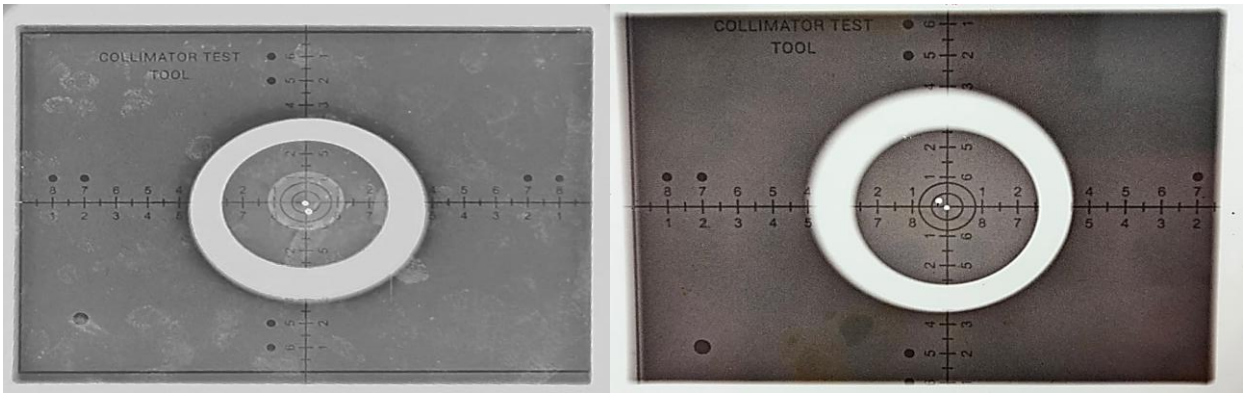
Table 1. Collimation alignment (field congruence) results evaluated against the 2% single-axis limit (SID = 100 cm).

Centre	Device Type	Start Date	X1 (cm)	X2 (cm)	Y1 (cm)	Y2 (cm)	Limit (2%)	Result
A	Toshiba	2020	-0.50	+0.15	+0.10	-1.25	≤ 2.0 cm	Pass
B	IAE	2012	-0.27	-0.55	-1.36	+0.45	≤ 2.0 cm	Pass
C	Fujifilm	2023	0.00	+0.25	+0.33	+0.50	≤ 2.0 cm	Pass
D1	GE	2019	-0.15	-0.55	-0.57	-1.40	≤ 2.0 cm	Pass
D2	Philips	2013	+0.32	-0.30	-0.50	0.00	≤ 2.0 cm	Pass
D3	Hitachi	2022	-1.50	-0.15	-0.65	-1.05	≤ 2.0 cm	Pass

(Table 2) summarises the absolute axis deviations (ΔX and ΔY) and the total combined misalignment (ΔX + ΔY) under the 4% regulatory limit. Across the evaluated sample, the mean absolute misalignment was 0.78 ± 0.47 cm (range: 0.25–1.65 cm) along the horizontal axis (ΔX) and 1.36 ± 0.58 cm (range: 0.50–1.97 cm) along the vertical axis (ΔY). The overall combined misalignment (ΔX + ΔY) averaged 2.14 ± 0.91 cm. Unit C (commissioned in 2023) achieved the highest congruence accuracy with a combined deviation of 1.08 cm (Figure 2a), whereas unit D3 (commissioned in 2022) recorded the highest combined deviation at 3.35 cm (Figure 2b). Consequently, all six units satisfied the < 4.0 cm international criterion, yielding a 100% pass rate.

Table 2. Collimation alignment (field congruence) results evaluated against the 4% combined-axis limit (SID = 100 cm).

Centre	Device Type	Start Date	ΔX ± 0.05 (cm)	ΔY ± 0.05 (cm)	ΔX + ΔY (cm)	Limit (4%)	Result
A	Toshiba	2020	0.65	1.35	2.00	< 4.0 cm	Pass
B	IAE	2012	0.82	1.81	2.63	< 4.0 cm	Pass
C	Fujifilm	2023	0.25	0.83	1.08	< 4.0 cm	Pass
D1	GE	2019	0.70	1.97	2.67	< 4.0 cm	Pass
D2	Philips	2013	0.62	0.50	1.12	< 4.0 cm	Pass
D3	Hitachi	2022	1.65	1.70	3.35	< 4.0 cm	Pass



(a) **(b)**

Figure 2. Representative radiographic images of light-to-X-ray field congruence: (a) Unit C (optimal alignment), and (b) Unit D3 (maximum observed deviation within tolerance limits)

Central Ray Beam Perpendicularity

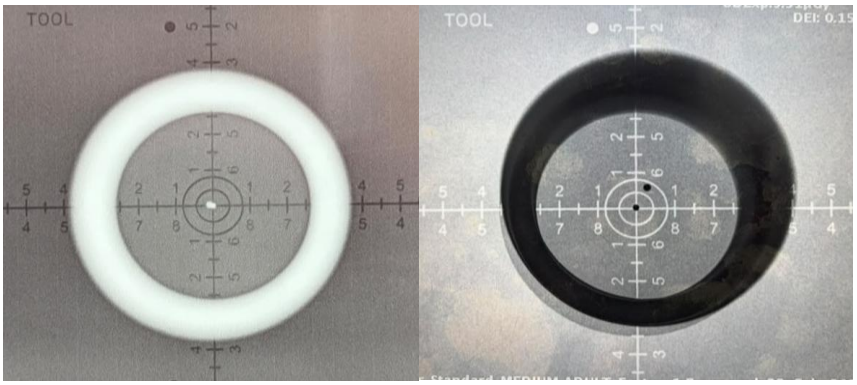
(Table 3) presents the visual assessment of the steel attenuator ball shadow projections and the corresponding angular deviations from true verticality. Five of the six evaluated units (83.3%) maintained angular deviations at or below 1.5°: units B and D2 exhibited near-coincident ball shadows (0.5°; Figure 3a), unit D3 demonstrated a minimal deviation (< 1.5°), and units C and D1 touched the outer boundary of the first reference ring (1.5°). Unit A exhibited the largest angular tilt, with the upper ball shadow approaching the inner edge of the second reference ring (1.5° < θ < 3°; Figure 3b), remaining just within

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the regulatory ceiling of < 3°. Overall, all six X-ray units passed the central ray perpendicularity test.

Table 3. Central ray beam perpendicularity test results across evaluated X-ray units.

Centre	Steel Balls Shadow Observation	Measured Angle	Limit (< 3°)	Result
A	Near inner edge of the second circle	< 3°	< 3°	Pass
B	Nearly coincident	0.5°	< 3°	Pass
C	Touching outer edge of the first circle	1.5°	< 3°	Pass
D1	Touching boundary of the first circle	1.5°	< 3°	Pass
D2	Coincident	0.5°	< 3°	Pass
D3	Slight deviation	< 1.5°	< 3°	Pass



(a) **(b)**

Figure 3. Representative radiographic images of central ray beam perpendicularity: (a) Unit D2 (optimal vertical alignment), and (b) Unit A (maximum observed angular tilt within tolerance limits)

Discussion

The empirical evaluation of six diagnostic X-ray machines across four public healthcare centres in Misurata city demonstrated a 100% compliance rate with international quality control standards for both light-to-X-ray field congruence and central ray perpendicularity. These findings reflect sound mechanical stability in the collimator shutter assemblies, accurate positioning of the 45° reflecting mirrors, and proper alignment of the light-field bulb filaments relative to the anode focal spots [11, 14]. Notably, older units commissioned in 2012 and 2013 (units B and D2) performed comparably to newer units installed in 2022 and 2023 (units D3 and C), indicating that sustained geometric integrity depends primarily on proper operational handling and periodic calibration rather than equipment age alone. A closer examination of the congruence data reveals two noteworthy physical patterns. First, the predominance of negative edge displacements indicates that the actual X-ray radiation field was marginally smaller than the visual light field across most units. From a radiation protection standpoint, a slight negative offset within the 2% tolerance threshold acts as a protective buffer that prevents unnecessary irradiation of adjacent healthy tissues without causing anatomical cutoff. Second, the mean misalignment along the vertical axis ($\Delta Y = 1.36 \pm 0.58$ cm) was nearly double that of the horizontal axis ($\Delta X = 0.78 \pm 0.47$ cm). This directional asymmetry is commonly attributed to mechanical wear and gravitational torque exerted on the collimator blades and mirror assembly during frequent vertical tube-stand adjustments. The field congruence results obtained in this study align closely with those reported by Akaagerger et al. [7], Saidu et al. [8], and Suandayani et al. [9], who observed single-axis deviations ranging between 0.23% and 1.14%—all well within the 2% international limit.

Conversely, our findings contrast with those of Metaningrum and Putro [10], who documented severe collimation misalignments exceeding 6% along the Y-axis due to mechanical drift, underscoring the clinical necessity of periodic QC verification. Maintaining accurate collimation prevents anatomical cutoff, eliminates repeat exposures, reduces scatter radiation reaching the image receptor, and directly lowers patient radiation doses in accordance with the ALARA principle [18–21]. Additionally, minimising retakes optimises departmental workflow and preserves operational resources such as X-ray tube lifespan and detector efficiency. Regarding central ray perpendicularity, all six units exhibited angular deviations below the 3° regulatory threshold [17], corroborating the geometric stability reported by Utomo et al. [5]. While five units (83.3%) demonstrated minimal angular deviations (≤ 1.5°), unit A approached the 3° upper boundary. Although classified as passing, such borderline alignment warrants proactive preventive maintenance and mechanical recalibration of the tube-stand detents to prevent progressive geometric distortion and loss of spatial resolution. Finally, certain methodological limitations specific to the scope of this investigation should be acknowledged. First, edge displacement and shadow alignment readings relied on manual and visual measurement techniques at the standard diagnostic distance (SID = 100 cm), which, although compliant with international protocols, offer lower sub-millimetre precision than automated digital image-analysis tools. Second, the sample size was restricted to six X-ray units across four public facilities in Misurata city, limiting statistical generalisation across wider regional healthcare facilities. Third, as a cross-sectional evaluation conducted between February and April 2026, the results represent a single-time-point operational snapshot rather than longitudinal mechanical drift over extended clinical workloads.

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Conclusion

This empirical study comprehensively evaluated the quality control performance of six conventional diagnostic X-ray machines across four public healthcare facilities in Misurata city by assessing light-to-X-ray field congruence and central ray beam perpendicularity. The key conclusions derived from this investigation are summarised as follows:

High Collimation Precision

All evaluated X-ray units demonstrated full compliance with international standards for light-to-X-ray field congruence, successfully satisfying both the 2% single-axis (≤ 2.0 cm) and 4% combined-axis (< 4.0 cm) deviation limits, with a 100% pass rate. The observed predominance of slight negative edge offsets indicates an operationally safe margin that protects patients from excess radiation without causing anatomical cutoff.

Geometric Accuracy

Central ray perpendicularity evaluations confirmed that all tested units maintained angular deviations strictly within the international safety threshold (< 3°), ensuring minimal geometric magnification and preserved spatial resolution across clinical examinations.

Radiation Protection and Workflow Safety

The complete absence of test failures underscores satisfactory equipment maintenance and operational integrity within the surveyed public facilities. These empirical findings directly support diagnostic reliability and reinforce the ALARA (As Low as Reasonably Achievable) principle by minimising patient radiation doses resulting from improper collimation or repeat exposures. Overall, while current performance levels in the surveyed centres are highly satisfactory, the implementation of periodic quality control protocols and proactive preventive maintenance for borderline alignments (such as Unit A) remain essential to sustaining long-term operational excellence and radiation safety in diagnostic radiology.

Author Contributions

All authors have made a substantial intellectual contribution to the work and approved it for publication.

Conflicts of Interest

The authors declare no conflicts of interest.

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