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Comparison of electronic portal imaging device-based Winston–Lutz analysis software

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Background: Stereotactic radiosurgery (SRS) with a linear accelerator requires submillimetre geometric accuracy. The Winston–Lutz (WL) test verifies coincidence among radiation, mechanical, and imaging isocentres. While portal imaging (EPID)-based WL methods offer rapid assessments, results may depend on image quality, ball bearing (BB) size, field size, and software algorithms.

Aim: To systematically compare commercial and open-source WL analysis software under varying imaging conditions.

Setting: Multiple radiotherapy centres across Western Cape South Africa. Utilizing Varian Trilogy and Elekta Versa HD linear accelerators.

Methods: Megavoltage (MV) EPID images were acquired on a Varian Trilogy (150 cm SID) and Elekta VersaHD (160 cm SID) using 6 MV flattened beams across multiple gantry and couch angles. Field sizes 10 cm × 10 cm, 6 cm × 6 cm and 2 cm × 2 cm and BB diameters 8 mm, 5 mm and 3 mm were tested. Images were analysed using Physikalisch-Technische Werkstätten (PTW) IsoCheck v1.2, SNC Machine v2.0.6, DoseLab Pro v7.0.0, PIPSpro Stereotactic v5.0.0, and PyLinac v2.2.6. Evaluated metrics included maximum total delta, 3D isocentre displacement, and isocentre diameter.

Results: Processing success and accuracy varied by BB size, field size, and linac type. Most software failed on Elekta VersaHD images with a 3 mm BB, except DoseLab, which succeeded in all cases. On Trilogy, smaller fields yielded smaller deltas; the inverse occurred on VersaHD (neither trend was statistically significant). SNC Machine exhibited the largest delta variation (Coefficient of Variation [CoV]: 19% – 114%), while DoseLab was most consistent (CoV: 1% – 6%). IsoCheck and PyLinac yielded comparable isocentre diameters when processing succeeded, with optimal consistency at 5 mm BB (Trilogy) and 8 mm BB (VersaHD).

Conclusion: The WL test outcomes depend on software, BB size, and imaging geometry. Preprocessing flexibility enhances robustness, and using larger BBs (5 mm – 8 mm) and mid-sized fields (~6 cm × 6 cm) improves detectability. When the 3D isocentre shift is minimised, maximum total delta can reflect the isocentre target error, but understanding software-specific definitions remains critical for SRS quality assurance (QA).

Contribution: This study compares the performance of different WL software when analysing the same images.

Keywords: EPID; Winston–Lutz; linac isocentre; stereotactic; quality assurance.

Introduction

The stereotactic radiosurgery (SRS) procedure with a linear accelerator (linac) uses small fields to deliver substantially high doses in 1–5 fractions of photon radiation to small, precisely located target volumes; and require stringent machine performance and quality assurance (QA) tests. Even a slight misalignment of the radiation isocentre can produce clinically significant geographic misses or dose shifts. The 'Winston–Lutz' (WL) test was introduced by Wendell Lutz, Kenneth Winston and N. Maleki when they published their linac-based SRS description in 1988.[1] The work formalised a practical, image-based method to verify that the radiation isocentre coincides with the mechanical isocentre used for patient localisation and treatment.

The classic WL approach places a small radio-opaque sphere (a ball-bearing phantom, ball-bearing [BB]) at the linac isocentre. The phantom is then irradiated from multiple gantry, collimator and couch angles (originally with film) and the offset is then measured between the projected BB centre and the centre of the radiation field for each beam. The combination of

Note: Additional supporting information may be found in the online version of this article as Online Appendix 1.

offsets quantifies the size and position of the radiation isocentre and reveals gantry, collimator and couch sag, misalignment or problems with the multi-leaf collimator (MLC) – all of which can drift with time or after a service or major repair.[2] For cranial SRS, the combined imaging-treatment coincidence and couch positioning tolerances are typically quoted at ≤ 1.0 mm. These stringent tolerances are the reason why the WL test is a cornerstone of regular SRS QA and therefore ensures the geometric accuracy of patient treatments.[3,4]

Modern implementations utilise the Megavoltage (MV) on-board electronic portal imaging devices (EPIDs) instead of film, as well as automated image analysis, to determine the radiation isocentre size and its coincidence with the laser and imaging systems used for patient localisation. The use of these electronic methods results in faster, higher-precision analysis and long-term trend tracking, and recent publications have shown sub-millimetre repeatability with these EPID-based WL workflows.[5,6] The cost and time-saving benefits of EPID-based WL analysis also introduce new challenges, which include:

i. The need to purchase analysis software, which can be expensive, independent of being a one-time cost or over the long term, if it's a subscription license.
ii. The potential for EPID image quality and resolution to affect the analysis and its results.
iii. Imaging limitations because of collision restrictions with certain gantry and couch combinations.
iv. Each software's proprietary algorithm for detecting the ball bearing (BB) and field edges may produce inconsistent results between different platforms.
v. That each software has its own definition of the WL and the radiation isocentre's 2D or 3D position.

Du, et. al. noted that the concept of the WL test is simple, but the radiation isocentre coincidence accuracy and size may be interpreted differently.[5] The most common interpretations include:

- The BB is mounted in an optimised position such that it is centred inside all radiation imaged fields, accounting for the wobble of the fields during gantry and collimator rotations, and mechanical imperfections during couch rotation. The concept of 'centred inside' could be interpreted as the maximum or mean offset of the ball from the centre of the image should be within a predefined tolerance limit for all images. Some softwares indicate the shifts required to move to this optimised position,[7] which is then regarded as the true radiation isocentre. It is furthermore required to calibrate the patient position system (lasers, imaging or surface guidance) to align with this position.
- Positioning the BB at the mechanical, laser or imaging isocentre and then the BB offset from the radiation isocentre is interpreted as the misalignment between the corresponding point (mechanical or imaging isocentre) and the true radiation isocentre.
- Lastly, this true radiation isocentre can be defined as the arithmetic mean of the individual field centres and the radius as the distance from this centre to the image centre farthest away, or
- The centre is defined by the origin of the smallest sphere encompassing all measurement points (minimising the average 2D error between the centre and the measurement points).

It was also mentioned that the choice of radiation field size can impact the WL results. Small fields are convenient for visual checks of the concentricity of the BB and radiation field, while larger fields allow more accurate localisation of radiation field edges. Additionally, the radiation field edges may be affected by the tongue-and-groove design of the MLC.

While various authors have tested WL phantoms and analysis methods,[6,8] the performance of the available software platforms warrants further investigation. The present study, therefore, seeks to investigate the inter-software agreement of different commercial and open-source WL EPID analysis software and determine their sensitivity to variations in image quality, BB marker size and radiation field dimensions. It is not the aim to determine the absolute accuracy of the software, and while minor inter-software variability is inevitable because of the proprietary nature of their analysis algorithms, it is expected that software designed towards a singular application and which analyses the same images should produce similar results and respond in the same way.

Methods

Electronic portal imaging device images of the BB phantom using the MV detector of a Varian Trilogy (aS1000 @ 150 cm SID, MilleniumHD120 MLC) and Elekta VersaHD (EOS iViewGT @ 160 cm SID, Agility MLC) were acquired with their 6 MV flattened beams at gantry angles of 0°, 90°, 270° and 180°.

The Varian HD120 MLC features 120 leaves (60 pairs). The central 8.0 cm region utilises 2.5-mm leaf widths to provide high-resolution modulation, while the peripheral regions use 5.0 mm leaves. This design employs rounded leaf ends, which necessitates specific dosimetric modelling (such as the dosimetric leaf gap) to account for the partial transmission through the leaf tips.[9] The Elekta Agility MLC consists of 160 interdigitating tungsten alloy leaves, each providing a 5.0-mm projected width at the isocentre. It utilises a combination of rounded and tilting leaf technology. The tilting mechanism allows the leaves to remain focused towards the radiation source, maintaining a more consistent penumbra across the entire 40 × 40 field.[10]

For each set of gantry angles, MLC field sizes of 10 cm × 10 cm, 6 cm × 6 cm and 2 cm × 2 cm were used, along with varying BB diameters of 8 mm, 5 mm and 3 mm. For each set of field sizes and BBs, images were also acquired at couch angles of 0°, 315°, 270°, 45° and 90° with the gantry at 0° (upright). This produced 12 gantry images in total and 15 couch images in total for each BB size and machine.

The same set of acquired EPID Digital imaging and communications in medicine (DICOM) images was analysed using the following software: Physikalisch-Technische Werkstätten (PTW) IsoCheck v. 1.2, Sun Nuclear (SNC) Machine v. 2.0.6, Mobius Medical Systems DoseLab Pro v. 7.0.0, Standard Imaging PIPSpro Stereotactic v. 5.0.0 and PyLinac v. 2.2.6 software. The results were then compared. In each software, the maximum total delta and 3D isoshift were obtained for each field size, BB size and Linac. The median value between the software was calculated, including the mean, standard deviation and coefficient of variation for each BB combination.

Ethical considerations

This article followed all ethical standards for research without direct contact with human or animal subjects.

Results

The PIPSpro analysis only reports the 2D planar radiation-mechanical isocentre offsets for each image and a 3D test that calculates an 'Optimal Isocentre Shift'. DoseLab Pro additionally reports the maximum absolute horizontal or vertical 2D delta observed in the set of images, as well as the maximum and the mean total delta (sum of horizontal and vertical deltas in quadrature). These values must be manually calculated for PIPSpro. Sun Nuclear Machine similarly reports the individual 2D deltas, the maximum delta observed in each set, and the maximum total delta overall, along with the 3D offset.

PyLinac reports the maximum, median and mean 2D deltas between the BB and the radiation field, considering all analysed images, along with the 3D shifts required to place the BB at the determined radiation isocentre. Additionally, it presents the 3D isocentre wobble diameter for the gantry and the 2D isocentre diameter for the couch and collimator, respectively, along with their associated maximum RMS deviation for each. PyLinac applies a back projection of the CAX in 3D and then minimises a sphere that touches all the 3D back projection lines (point [iv] above). It was observed that the maximum 2D delta and the maximum RMS value were similar. IsoCheck determines the diameter of the isocentre ball, the 3D isocentre position, the distance between the isocentre and the origin, the standard deviation and the standard error of the mean of the evaluated images, as well as the 2D deltas for the individual images either according to point iii or point iv as indicated by the user.

In Figure 1 and Table 1-A1 (Online Appendix 1), we present the maximum total delta for the same gantry WL images calculated by SNC Machine, DoseLab, PIPSpro and PyLinac and the different BB sizes, along with the median total delta of the software results. The median was used instead of the mean to minimise the influence of possible outlier values across software. Only the DoseLab software was able to detect and determine a delta for all field sizes using the 3 mm BB on the VersaHD linac, whereas PyLinac could not process any field size using the 3 mm BB on this linac.

The figures depict a negative regression with field size on the Varian Trilogy machine for all BB sizes: As the field size decreases, so does the reported maximum delta. This is consistent across all software, except SNC Machine, which showed the most inter-field variation among the evaluated software. On the Elekta VersaHD, the opposite trend is displayed: The maximum calculated delta increases with field size. However, a one-way ANOVA test showed no overall statistically significant field size dependence for each BB among the software (p = 0.2006, 0.1231 and 0.1207, respectively, for the Varian images and p = 0.0945, 0.0274 and 0.6997 for the Elekta images).

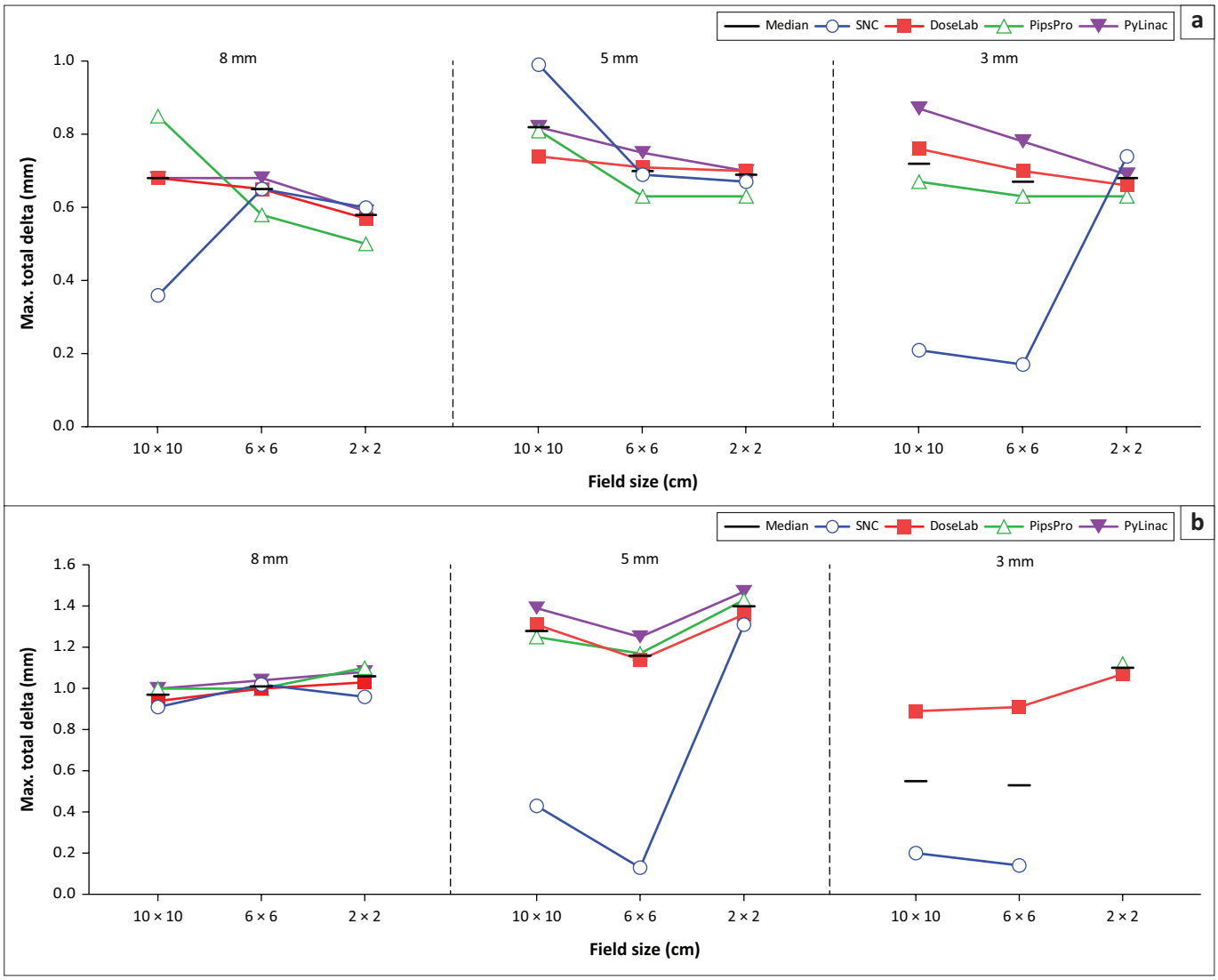
The SNC Machine software showed a large variation in delta results across all fields and BB size for the Varian Trilogy linac (Coefficient of Variation [CoV]: 19% – 70%), whereas DoseLab had the least (CoV: 3%) using the 5 mm BB. SNC Machine performed similarly for the Elekta VersaHD (CoV: 5% – 80%); however, most software (including SNC Machine) showed small variation (CoV 5%) and similar means (0.96 mm – 1.04 mm) when using the 8 mm BB.

In Figure 2 and Table 2-A1 (Online Appendix 1), we present the isocentre displacement (magnitude of the 3D shifts) for IsoCheck, SNC Machine, DoseLab, PIPSpro and PyLinac (which requires both gantry and couch images), along with the overall median displacement across the software.

The PTW IsoCheck software failed to process the images in some instances, particularly the 3 mm BB, for both the Varian Trilogy and the Elekta VersaHD linacs, whereas most other softwares were able to do so. Sun Nuclear Machine again showed the largest variation in results when changing field size (CoV: 11% – 114%), regardless of linac type. Physikalisch-Technische Werkstätten IsoCheck had the most consistent mean displacement result across field and BB size (mean: 0.26 – 0.28 mm) for the Varian Trilogy linac. However, the average mean displacement differed significantly (0.27 mm vs. 0.41 mm – 0.48 mm) from DoseLab, PIPSpro and PyLinac. DoseLab once again had the least variation in results (CoV: 1%) using the 5 mm or 3 mm BB on the Varian Trilogy; and using the 5 mm – 8 mm BB (CoV: 5% vs. 6%) on the Elekta VersaHD with the median displacement (0.46 mm – 0.59 mm) varying the least across software when using the 8 mm BB.

In Figure 3 and Table 3-A1 (Online Appendix 1), we present the gantry isocentre diameter (mm) as determined by the PyLinac and IsoCheck software (using the 'smallest sphere' method), along with the median calculated value.

IsoCheck failed to process the 3 mm BB on both the Varian and Elekta linacs, with PyLinac managing with only the Varian-acquired images. Both software packages had the most consistent results using the 5 mm BB on the Varian linac



SNC, Sun Nuclear; Max, maximum; mm, millimeter; cm, centimeter.

FIGURE 1: The maximum total delta (mm) (a) observed in gantry Winston–Lutz images for the Varian Trilogy and (b) Elekta VersaHD linacs, as calculated by SNC Machine, DoseLab, PIPSpro and PyLinac, for 8 mm, 5 mm and 3 mm BB.

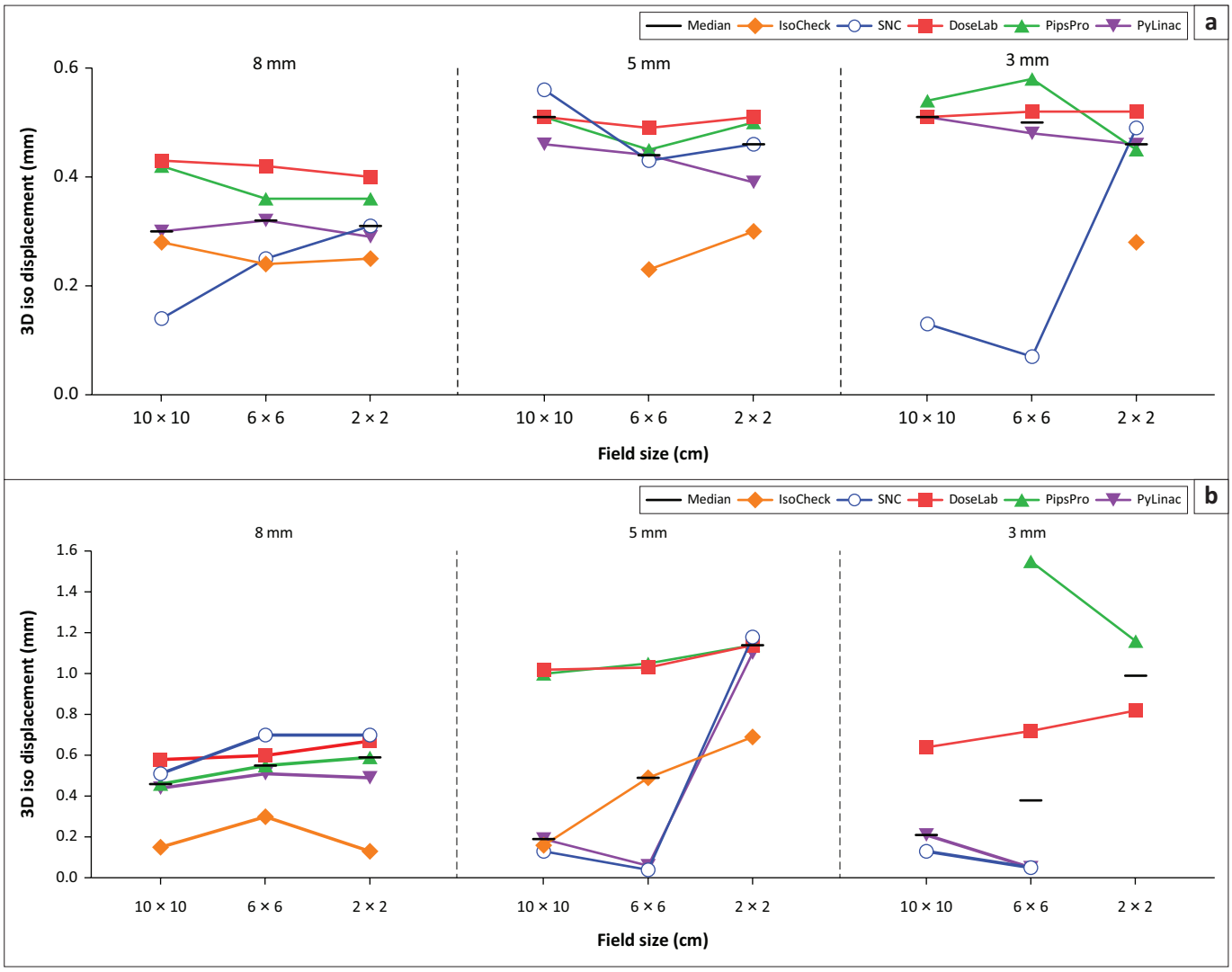
(mean: 0.86 mm – 0.87 mm, CoV: 2%) and the 8 mm BB on the Elekta linac (mean: 0.97 mm – 1.18 mm, CoV: 4% – 6%) across the tested field sizes.

Discussion

Similar to our observation, Du, et al. found that the field size had no statistically significant effect on the radiation isocentre deltas when investigating the WL test accuracy using in-house software and the SunCHECK WL Isocentre QA software on a Varian TrueBeam linac.[5]

The image quality and clinical utility of the Varian and Elekta EPID images are influenced by distinct hardware configurations and scaling protocols. While both vendors utilise amorphous silicon technology, their physical geometries differ. (Varian aS1000 features a 1024 × 768 pixel matrix with a 0.39 mm pixel pitch, and the Elekta iViewGT has a 1024 × 1024 pixel matrix with a 0.40 mm pixel pitch.) Although Elekta employs a larger matrix, the resulting pixel resolution remains comparable to Varian's because it is distributed over a larger physical field of view. Consequently, the native spatial resolution of both detectors is essentially equivalent for clinical applications. Digital imaging and communications in medicine scaling acts as a linear transformation that does not inherently degrade the raw image data. It maintains the integrity of the results through the signal-to-noise ratio (the scaling applies the same multiplier to both signal and noise, keeping the ratio constant) and the spatial integrity (the physical dimensions and the number of pixels remain unchanged by scaling factors, ensuring that the geometric representation of anatomy is preserved).

The most significant operational difference lies in the available SID. Utilising a larger SID may enhance results through increased magnification – at a larger SID, a greater number of pixels represent the BB, supposedly allowing software algorithms to calculate the centroid with higher mathematical precision; however, increasing the SID increases the geometric penumbra of the field edge and of the BB, 'blurring' the image. This can negatively affect the ability



SNC, Sun Nuclear; mm, millimeter; cm, centimeter.

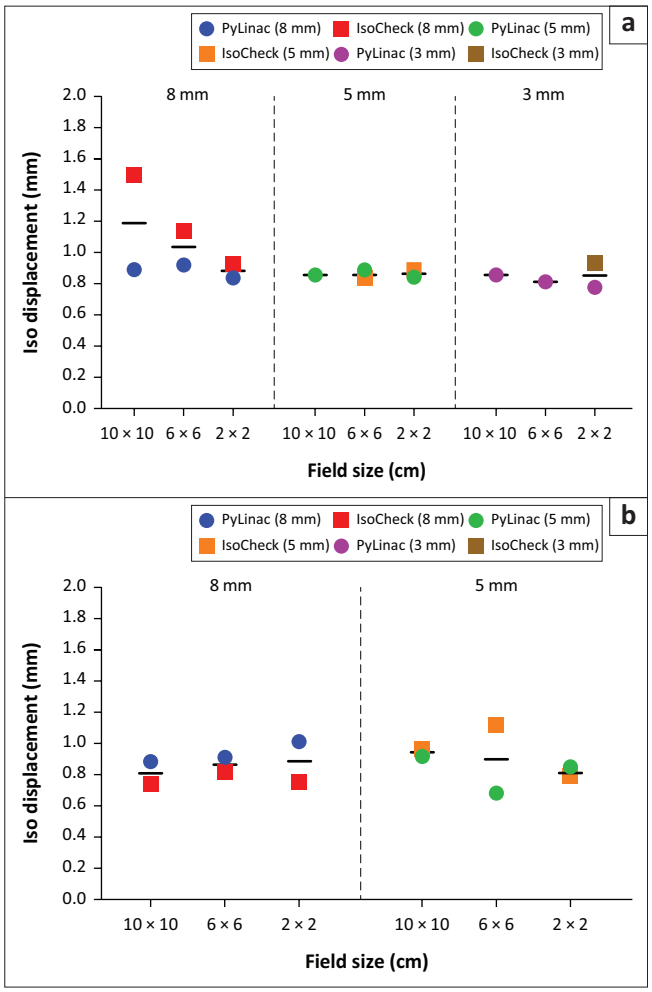
FIGURE 2: The absolute 3D shift to iso (mm) (a) observed in Winston–Lutz images for the Varian Trilogy and (b) Elekta VersaHD (bottom) linacs, as calculated by IsoCheck, SNC Machine, DoseLab, PIPSpro and PyLinac, for 8 mm, 5 mm and 3 mm BB.

of the analysis software to define the field and radiation isocentre, increasing the uncertainty of the final delta results.

The failure of most software to detect and process the WL images using the 3 mm BB, particularly for the Elekta VersaHD, which is acquired at a fixed SID of 160 cm, compared to the 150 cm SID on the Varian linac, indicates the dependence of the software on image quality. Our observations indicate that decreasing the distance between the BB and the imaging device decreases the chance of image processing failures. Additionally, the software, which was usually successful, like DoseLab and PIPSpro, also has the functionality to edit the image parameters (window level, region of interest (ROI) and zoom) before WL processing.

DoseLab can load between 1 and 25 images, and the WL tool automatically selects ROIs that correspond to each exposure. Each ROI is automatically labelled with the field name tagged in the DICOM image or with the image's file name, and ROI selections can be added or deleted. DoseLab also allows the user to adjust the radiation field and centre object thresholding to better determine the field and BB edges. A pattern is noticed with the SNC software compared to the other software: it appears to be susceptible to smaller field sizes and a smaller BB, leading to increased variation in results. This is likely because the software needing to apply a thresholding or edge detection algorithm to distinguish between the intensity of the BB and the surrounding image. A smaller field and smaller BB may result in it being more challenging to differentiate between the BB and its surroundings.

As briefly mentioned above, the PIPSpro analysis is limited to a maximum of eight images (usually four gantry angles and four couch angles) and reports the 2D planar radiation-mechanical isocentre offset error for an individual image, which is calculated as the offset of the BB from the centre of the image. The 3D 'Optimal Isocentre Shift' represents a vector that, if applied to the BB, would result in better results on average. This vector can indicate a number of things, including errors in ball setup, misalignment of lasers or the light field or actual radiation-mechanical isocentre offsets. The 2D delta values are the definitive QA values for



mm, millimeter; cm, centimeter.

FIGURE 3: The reported gantry isocentre diameter for the (a) Varian Trilogy and Elekta VersaHD linacs, as calculated by PyLinac and (b) IsoCheck for the 8 mm, 5 mm and 3 mm BB, with the median value for each field size indicated.

representing isocentre target error (i.e. the mechanical, lasers or imaging setup vs. the radiation isocentre). Nonzero 3D target position values only represent a potential positioning improvement of the target to minimise the average 2D error, not necessarily an ability to eliminate 2D error.

Therefore, if you align the BB to the optimal radiation isocentre (or if you trust your setup with the imaging iso or lasers and continue with the position as is, the 'isocentre'), then the total delta value represents the maximum deviation of the radiation isocentre around all of the points (i.e. the diameter of the radiation sphere). PTW IsoCheck and PyLinac directly report the isocentre diameter and its origin in 3D coordinates. This iterative procedure of aligning the BB to the optimal radiation isocentre is used by Elekta when determining MV isocentre size and calibrating the kV flex-maps and lasers.

When analysing the gantry radiation isocentre, the use of a single collimator angle can lead to systematic errors from collimator misalignment in one direction – a common practice is to use opposite collimator angles (such as 90° and 270°); however, residual systematic errors may exist because of gravitational effects on the collimator, and therefore using oblique opposite or mixed collimator angles can reduce this effect in future investigations and routine QA.[5,11]

Collimator rotations were excluded from this comparative analysis, as the study's primary objective was to evaluate the inter-software agreement and the sensitivity of the analysis software to variations in image quality, BB diameter and radiation field dimensions. Gantry-rotated images should provide a sufficient data set to establish these fundamental trends. While the inclusion of collimator-angled images would introduce additional sampling angles, this additional geometry does not provide further insight into the specific parameters under investigation. It is anticipated that the software's systemic response to image quality and marker size remains consistent regardless of the collimator's orientation; therefore, a different projection would not significantly alter the established correlations.

The choice of analysis software and the interpretation of the results they produce may also be guided by the local interpretation of the radiation isocentre and limits. The AAPM, ACR and ASTRO recommend that up to ± 1 mm deviation between the radiation and mechanical isocentre is acceptable for SRS and SRT treatments.[3] The IAEA states that the collimator axis of rotation, the gantry axis of rotation and the treatment table axis of rotation should all intersect in a sphere. The radius of this sphere determines the isocentre uncertainty. This radius should be no greater than 1 mm, and for machines used in radiosurgery should not exceed 0.5 mm.[12] However, the tolerance of < 0.5 mm radius is not achievable by most C-arm linac manufacturers. The German DIN (Deutsches Institut für Normung) require the reporting of the radius (in mm) of the isocentre sphere, which is the smallest sphere through which the central ray of the radiation beam runs for all gantry and table rotation angles; and that the deviation of the geometrical and radiation isocentre from the optical indication of the isocentre must be specified (in mm) in three orthogonal planes within the room coordinate system.[13]

Furthermore, as a single isocentre, multiple-target SRS (treating many small lesions with one isocentre) has become more common, and off-isocentre WL variants were developed to quantify how the radiation-mechanical congruence degrades away from the central isocentre (and to select safe off-axis distances for gantry and collimator angle sets).[14,15] These off-isocentre WL methods are now active topics of research and clinical commissioning, and specialised software has been developed to perform and report on this testing.

Limitations

This study did not include additional repeated measurements and evaluations in the assessment of intra-software variability; however, much care was taken during the setup of the WL tests based on locally approved standards, and the measurements were not benchmarked against a recognised golden standard for absolute accuracy. The findings are

based on a limited sampling angles and a constrained dataset. The conclusion on the effect of SID is based on the comparison between two distances.

Conclusion

Clinical interpretation of Winston–Lutz results requires discretion by a qualified medical physicist. The maximum total delta presents as a proxy for isocentre uncertainty, provided the 3D isocentre shift is minimised. To optimise detectability – particularly when the SID cannot be adjusted – it is recommended to use a larger ball bearing (5 mm – 8 mm) in conjunction with an intermediate field size (~6 cm × 6 cm).

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Competing interests

The authors, Hein Fourie; Carolien de Ridder and Sakhele Shiba, declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article.

CRediT authorship contribution

Hein Fourie: Conceptualisation, Data curation, Formal analysis, Resources, Software, Visualisation, Writing – original draft and Writing – review & editing. Carolien de Ridder: Software, Validation and Writing – review & editing. Sakhele Shiba: Software, Validation and Writing – review & editing. All authors reviewed the article, contributed to the discussion of results, approved the final version for submission and publication and take responsibility for the integrity of its findings.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article and/or its supplementary materials.

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