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Positions of radiation isocenter and the couch rotation center established by Winston-Lutz and optical measurements

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ABSTRACT

Purpose: To compare x-ray and optical imaging methods for measuring the relative position of radiation isocenter and couch rotation center. To show the impact of radiation isocenter size and target motion on the margins for target contours.

Methods: Winston-Lutz measurements are made using EPID images. Image analysis was done with public domain software, ImageJ, and spreadsheets written in Microsoft Excel. A comparison between the center of a high density test object and center of the MLC collimated beam is used to judge the relative position of the radiation isocenter in space for gantry and couch rotation. Additionally, motion of the target with couch rotation is determined with an optical imaging system. Five different accelerators, two TrueBeams, a Trilogy, and two VersaHDs, were assessed by Winston-Lutz and optical methods.

Results: The shift in the radiation isocenter with gantry rotation is found to be a tri-axial ellipsoid. Shifts in the target position with respect to radiation isocenter with couch rotation were between 0.4 and 0.6 mm. The Winston-Lutz and optical method determination of couch rotation center agreed within measurement uncertainty.

Conclusions: Image analysis yields precise data on linear accelerator radiation isocenter and rotation centers of the couch. The Winston-Lutz and optical methods agreed within measurement uncertainty.

Introduction

A linear accelerator has a mechanical center of rotation and a radiation isocenter that is the average position of the radiation beam that results from all of the mechanical variations as the machine gantry rotates. The recommendation for machines used to treat stereotactic radiosurgery (SRS) [1] and stereotactic body radiotherapy (SBRT) [2,3] is that the maximum deviation between mechanical and radiation centers is ± 1 mm [4,5]. The radiation isocenter is a nexus of points established by the intersection of the central axis of the radiation beam as it rotates with gantry angle. These shifts are a consequence of the movement in space of the collimator delimitation of the beam, which occurs because the gantry bends and twists under the force of gravity. Additionally, the couch and, consequently, the patient target, shift in space with couch angle because the rotation axis of the couch is not coincident with the radiation isocenter established by the gantry rotation [6]. The walkout of the target at different couch angles is completely characterized by the Winston-Lutz method [7] with the gantry kept at angle zero.

A common task in linear accelerator quality assurance, QA, [3] is the measurement of the radiation isocenters defined by collimator, gantry, and couch rotations. Methods to measure these isocenters that have used radiographic film, colloquially called "star shots", have been in use for decades [8]. The use of radiographic film is time consuming, requires film-processing equipment, and must use film scanning-equipment to convert the film density into digital data. These disadvantages of film are avoided by the use of electronic portal imagining devices (EPID) [9] which have now become commercially available on all linear accelerators.

More than a decade ago [10,11,12,13] the usefulness of EPIDs as a physics tool was recognized and they were used for measurements of beam penumbra, radiation versus light field coincidence, and center of collimator rotation. EPIDs have also been used instead of film for mechanical alignment [14] and radiation isocenter assessment [11,15,16,17] of linear accelerators.

In the present study an EPID is used to determine the radiation

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Fig. 1. Styrofoam head phantom mounted on the end of an accelerator couch.

isocenter defined by gantry rotation and the couch rotation center with the Winston-Lutz approach. Also, an optical approach that uses the AlignRT optical system is used to measure the couch rotation point and the shift in target with respect to the radiation isocenter as the couch is rotated.

Materials and methods

Epid based quality assurance system

An EPID based quality assurance, QA, procedure has been developed for QA tests in our clinics. QA images were taken with aS1200 EPIDs (Varian Medical Systems, Palo Alto, CA) and iViewGT a-Si EPIDs (Elekta AB, Stockholm, Sweden) that have the E-arm support positioning-arm. Five treatment machines were used, a Trilogy and two TrueBeam accelerators (Varian Medical Systems, Palo Alto, CA) and two VersaHD accelerators (Elekta AB, Stockholm, Sweden).

Data were acquired with 6 MV nominal beam energy. The QA images were taken with a 2 MU dose setting. Image analysis was done with ImageJ [18] public domain software and spreadsheets written in Microsoft Excel (Microsoft Corp., Redmond, Washington).

The method used was essentially that of the Lutz test [7]. The core of this method is to place a high-density test object (a 6 mm diameter metal sphere) at what is believed to be the radiation isocenter and to take images with EPID from different gantry angles. A comparison between the center of the test object and the collimated beam, which is delimited by the edges of a multileaf collimator (MLC) leaves, was used to judge the relative position of the radiation isocenter in space. The radiation isocenter with respect to the test object can be determined as can its position in the field at any gantry angle. Details of the method are given in Supplemental Materials.

The uncertainty in the Winston-Lutz method was tested in the following way. The couch was kept at 0° and was moved in 0.5 mm increments in the vertical, longitudinal, and lateral directions. The couch motions are done manually in float mode. The motion of the metal sphere, which was rigidly connected to the couch, was measured with respect to the MLC edges with the Winston-Lutz method. Further details are given in Supplemental Materials.

For the Winston-Lutz measurements there is uncertainty in the field position due to lack of reproducibility in the position of the MLC leaf ends. This was tested by measuring the MLC position with respect to the sphere for a 2 cm × 2 cm field for seven repeats with the MLC fully opened between repeated formations of the 2 cm × 2 cm field. The sphere is kept stationary in space.

Table 1
Standard deviation in the position of the MLC delimited radiation field center with respect to the sphere. Measurements are made at gantry at 0°.

Accelerator	Sup-Inf, mm	Left-Right, mm
TrueBeam 3455	±0.03	±0.14
TrueBeam 2928	±0.01	±0.15
Trilogy 1256	±0.02	±0.16
VersaHD1	±0.04	±0.03
VersaHD2	±0.03	±0.05

Optical based quality assurance system

Another measurement system that was used was based on optical images. In the treatment room an optical system that monitors surface images, AlignRT (VisionRT, London, UK) was used to setup the patient and monitor patient motion during treatment. This optical system has been described in the literature [19,20,21,22,23,24,25,26]. The system consists of three pods, which contain two cameras and a light projector, that monitors patient position during treatment. For internal cranial stereotactic treatments, these three pods captured a surface image of the open face of the patient, from different perspectives. AlignRT software combines these images of the patient's face to reconstruct a three-dimensional (3D) surface image of the patient. Movement of the surface image with respect to the optical isocenter of the AlignRT system was given in both linear and rotation directions [27,28].

The uncertainty in the AlignRT method was tested in a similar way as the Winston-Lutz method. The gantry was kept at 0°, a reference optical image was captured, and the couch was moved in 0.5 mm increments in the vertical, longitudinal, and lateral directions. The motion of the head phantom, which was rigidly connected to the couch as shown in Fig. 1, was measured with AlignRT.

For all AlignRT measurements the projection time was kept to less than two minutes to avoid offsets in optical coordinates due to heating [26] of the pods.

The optical isocenter of AlignRT was adjusted to be coincident with the radiation isocenter by use of a cube phantom [28]. This phantom has imbedded ceramic spheres that were imaged with the accelerator MV beam at four gantry positions and a Winston-Lutz method was used to determine radiation isocenter. The cube surface was imaged with AlignRT and its optical isocenter was adjusted to be coincident with the measured radiation isocenter. The coincidence of the AlignRT optical center and the linear accelerator radiation isocenter were checked daily before measurements were made.

For the measurements of couch motion, a Styrofoam head phantom was securely mounted to the couch, Fig. 1, and was imaged by the AlignRT system. The phantom was initially positioned with the isocenter near the center of the skull and a reference image was taken. AlignRT measurements of position were made for various couch rotation angle settings. These couch measurements can also be done using the AlignRT alignment cube.

Results

Measurement uncertainty

The uncertainty in the Winston-Lutz measurements as implemented here is found to be 0.16 mm. The uncertainty in the AlignRT measurements as implemented here is found to be 0.18 mm.

Epid based quality assurance system results

For the Winston-Lutz measurements there is uncertainty in the field

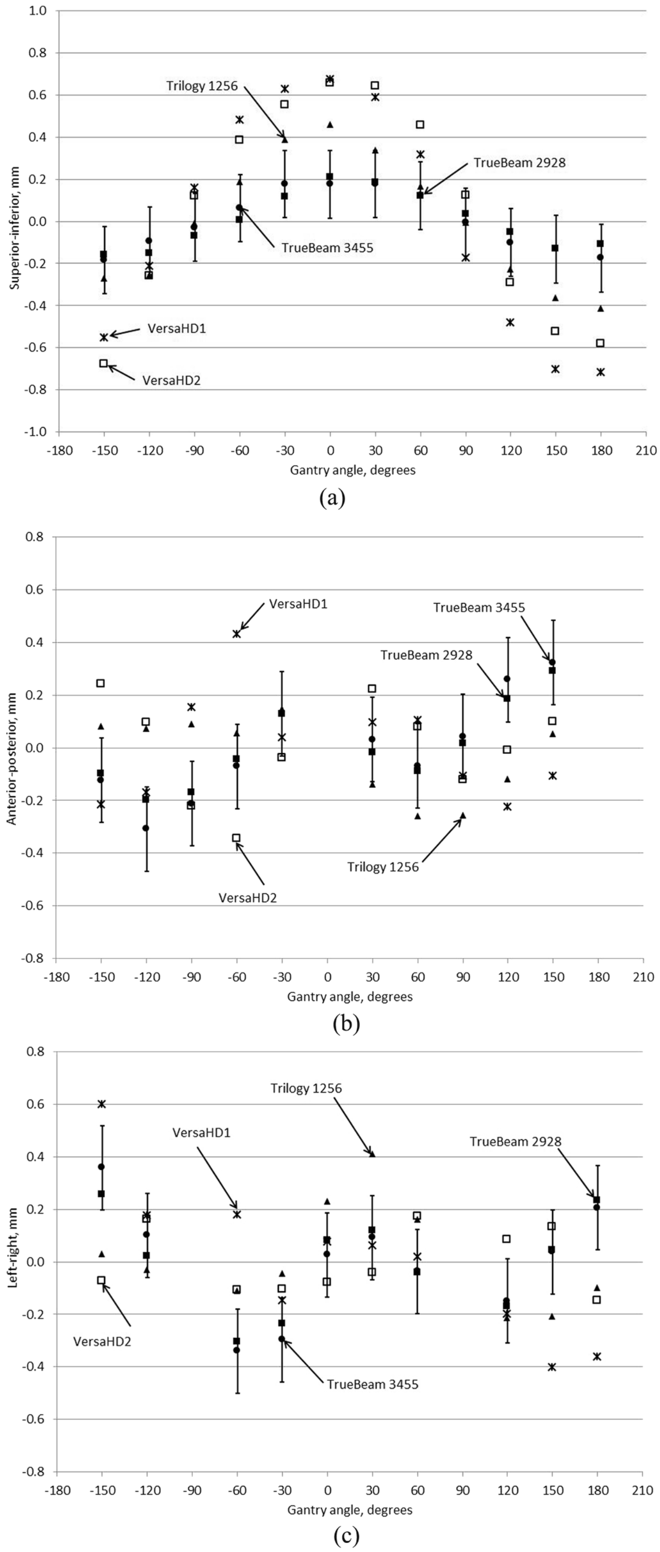

Fig. 2. Shift of MLC delimited field center with respect to the sphere versus gantry angle. a. is in the superior-inferior direction, b is in the anterior-posterior direction, and c. is in the left–right direction. The error bars indicate the uncertainty in this measurement method as explained in the text.

position due to lack of reproducibility in the position of the MLC leaf ends. Table 1 presents results for the different accelerators. The MLC leaves move in the left–right direction and the uncertainty of the leaf position is found to be $\leq \pm 0.16$ mm for all of the accelerator MLC systems.

Table 2
Shifts in MLC delimited radiation field center with respect to the sphere versus gantry angle.

Accelerator	Sup-Inf, mm	Ant-Post, mm	Left-Right, mm
TrueBeam 3455	−0.2 to + 0.2	−0.3 to + 0.3	−0.3 to + 0.3
TrueBeam 2928	−0.2 to + 0.2	−0.2 to + 0.3	−0.3 to + 0.3
Trilogy 1256	−0.4 to + 0.4	−0.4 to + 0.4	−0.4 to + 0.2
VersaHD1	−0.6 to + 0.6	−0.3 to + 0.4	−0.4 to + 0.6
VersaHD2	−0.6 to + 0.6	−0.2 to + 0.3	−0.5 to + 0.2

Table 3
Position of the radiation isocenter with respect to the center of the MLC defined field with the gantry at 0°.

Accelerator	Superior-Inferior, mm	Left-Right, mm
TrueBeam 3455	−021	0.06
TrueBeam 2928	−0.21	−0.08
Trilogy 1256	−0.46	−0.23
VersaHD1	−0.67	−0.08
VersaHD2	−0.65	0.08

Table 4
Position of the radiation isocenter with respect to the center of the MLC defined field with the gantry at 90°.

Accelerator	Superior-Inferior, mm	Anterior-posterior, mm
TrueBeam 3455	−0.03	−0.18
TrueBeam 2928	−0.04	−0.02
Trilogy 1256	0.01	0.26
VersaHD1	0.17	0.11
VersaHD2	−0.12	0.12

When the gantry is rotated, the position of the MLC edges and the radiation center of the beam will shift in space due to mechanical stress on the gantry structure from the force of gravity. The sphere remains stationary in space. Uncertainty of the MLC leaf position is not important since a 2 cm × 2 cm MLC delimited field is formed and not changed during the gantry rotation.

Analysis of the Winston-Lutz images indicates the shift in MLC delimited radiation field center with respect to the sphere versus gantry angle. Fig. 2a-2c show these field shifts in the superior-inferior, anterior-posterior, and left–right directions for single measurement sessions of five accelerators. These shifts are defined in the patient coordinate system with positive being superior, anterior, and left. The shifts in all directions are less than ± 0.3 mm for TrueBeam accelerators. The range of these shifts define the extent of the position of the radiation isocenter in 3D space as the gantry rotates by 360°. It is of interest that the shift in the superior-inferior direction, Fig. 2.a., is greatest at 0° and 180° gantry angle and smallest at 90° and −90°. Table 2 gives summary data for multiple measurement sessions of the five accelerators. The shifts in the MLC delimited field center for all of the machines are greater than the 0.16 mm uncertainty established for the Winston-Lutz measurement. The VersaHD accelerators have three-fold greater motion of the radiation isocenter in the superior-inferior direction than observed with the TrueBeam accelerators.

Based on the gantry rotation data the location of the radiation isocenter position in space is determined and is placed in the MLC defined field when the gantry is at 0°, Table 3, and when the gantry is at 90°, Table 4.

For all of the accelerators the radiation isocenter is inferior to the MLC delimited field center at gantry 0°. At gantry ± 90° the radiation isocenter is close to the center of the field for all of the machines. This is consistent with the data shown in Figs. 2.a.

When the couch is rotated, the position in space of the sphere will shift unless the sphere has been positioned coincidental with the couch

Table 5
Winston-Lutz measurement of the position of the couch rotation center with respect to the center of the MLC defined field with the gantry at 0°. Also, the distance between the radiation isocenter and the couch rotation point is shown.

Accelerator	Superior-Inferior, mm	Left-Right, mm	Radiation isocenter to couch rotation point distance, mm	Radiation isocenter to couch rotation point distance after couch adjustment, mm
TrueBeam 3455	0.58	−0.04	0.80	0.30
TrueBeam 2928	0.11	0.11	0.37	NA
Trilogy 1256	−0.33	−0.43	0.24	NA
VersaHD1	0.44	0.15	1.13	0.39
VersaHD2	−0.13	−0.12	0.56	0.28

rotation axis. Based on the motion of the sphere, which is determined by Winston-Lutz analysis, the couch rotation axis can be placed in the MLC defined field when the gantry is at 0°. Based on the couch rotation data the location of the couch rotation position in space is determined and placed in the MLC defined field when the gantry is at 0°, Table 5. The MLC delimited field is formed and not changed during the gantry rotation.

The couch rotation position is quite variable between machines. Comparing Tables 3 and 5 it is clear that the radiation isocenter is not coincident with the couch rotation center for any of the machines. The largest disparity between radiation isocenter and couch rotation center occurs for the TrueBeam 3455, VersaHD1, and HD2 machines, being greater than 0.5 mm. Based on these data the couch rotation positions with of the TrueBeam 3455, VersaHD1, and HD2 were adjusted to be closer to the radiation isocenters. After adjustment, the distance between radiation isocenter and the couch rotation center decreased to 0.30, 0.39 mm and 0.28 mm for the TrueBeam 3455, VersaHD1, and HD2, respectively, as shown in Table 5. This improvement was greater than 0.5 mm for the VersaHD1 machine.

Couch rotation measured with epid and optical systems

As a result of the lack of coincidence of the radiation isocenter and the couch rotation point, when the couch is rotated a target that is at radiation isocenter at couch angle 0° will rotate off isocenter at other couch angles. Fig. 3 shows how the target moves with respect to radiation isocenter for the TrueBeam 2928 accelerator with couch angle. At couch 0° the target is placed directly over isocenter at coordinates (0,0) and as the couch is rotated the target sweeps in a circle away from radiation isocenter. The solid line in Fig. 3 is calculated from the position of the couch rotation point with respect to the radiation isocenter as measured with the Winston-Lutz analysis. Also, the target motion with couch rotation is measured with AlignRT and these data are shown in Fig. 3. Within experimental uncertainty, the Winston-Lutz and AlignRT motion measurements agree. As the distance between the radiation isocenter to the couch rotation point increases, see the last column in Table 5, the shift in target position away from radiation isocenter will also increase at couch angles different from 0°.

Based on the couch rotation data measured with AlignRT the location of the couch rotation position in space is determined and placed in the MLC defined field when the gantry is at 0°, Table 6. The couch rotation position is quite variable between machines. Based on the

Table 6
AlignRT measurement of the position of the couch rotation center with respect to the center of the MLC defined field with the gantry at 0°.

Accelerator	Superior-Inferior, mm	Left-Right, mm
TrueBeam 3455 after gantry stand adjustment	−0.03	0.29
TrueBeam 2928	0.38	0.13
Trilogy 1256	−0.27	−0.35
VersaHD1 after couch adjustment	−0.43	0.33
VersaHD2 after couch adjustment	−0.73	−0.35

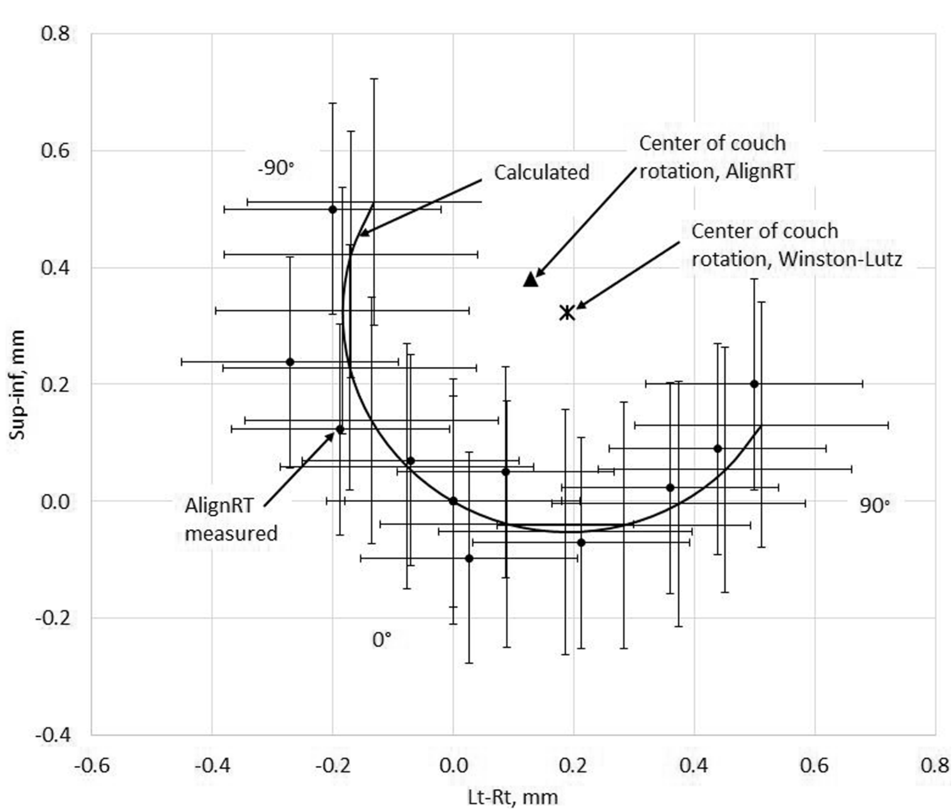

Fig. 3. Shift of the target in the MLC defined field, with respect to the radiation isocenter in the left–right and superior-inferior directions versus couch angle. Three primary couch angles are shown. The coordinate system is shifted so that radiation isocenter is at position 0,0 at couch angle 0°. AlignRT measured, ●, and Winston-Lutz calculated, solid line, data are shown. Couch rotation centers measured by Winston-Lutz (*) and AlignRT methods (▲) are shown. The error bars indicate the uncertainty in these measurement methods as explained in the text.

measurement uncertainty of Winston-Lutz and AlignRT the combined uncertainty will be ± 0.34 mm. Tables 5 and 6 show that the couch rotation center measured with Winston-Lutz and AlignRT agree within measurements uncertainty.

Discussion

Radiation iscenter shifts due to gantry rotation

The Radiation isocenter is defined by radiation field motion in space with gantry rotation. It was found for the five machines that were measured that changes with gantry rotation were as great as 0.7 mm in the superior-inferior direction for some of the machines. This radiation isocenter shift is due to altered direction of mechanical stress from gravity on the gantry at different angles. For all of the accelerators, the radiation isocenters are found to not be spheres but tri-axial ellipsoids, whose axis lengths are shown in Table 2.

The uncertainty in the Winston-Lutz measurements as implemented here is found to be 0.16 mm and for AlignRT 0.18 mm. These uncertainties compare well to the recommended ± 1 mm for SRS [4,5].

Radiation iscenter shifts due to couch rotation

The shift in the target position from radiation isocenter with couch rotation was as great as 0.78 mm. This is solely due to the center of rotation of the couch not being coincident with the radiation isocenter. A comparison between the Winston-Lutz method and the AlignRT optical method showed that they were in agreement within measurement uncertainty.

How the various measurements and uncertainties shown in this work are used to adjust target margins is shown in the Supplemental Materials.

Conclusions

Shifts in beam isocenter with gantry rotation are machine specific and are between 0.2 and 0.6 mm. Winston-Lutz and AlignRT optical methods give the same location for the couch rotation center within measurement uncertainty. The couch rotation center is not coincident with the radiation isocenter established by gantry rotation. Margins for GTV to PTV expansion are machine specific and must be ≥ 0.6 mm.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tipsro.2022.01.004.

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