Beam spot position measurement using corotational penumbra modulation and image center shift methods

Rofikoh¹, A Rafliansyah¹, Sugiyantari¹ and D S Soejoko²

¹Department of Radiotherapy, Persahabatan Central Hospital, 17222, Jakarta, Indonesia
²Department of Physics, University of Indonesia, 16480, Depok, Indonesia
rofikohuzma@gmail.com

Abstract. Image and treatment quality of radiotherapy are influenced by the position of beam spot, therefore it is important to know the position of the beam spot. Beam spot position measured by the corotational penumbra modulation (CPM) and the image center shift (ICS). The CPM method uses a cylindrical ion chamber that rotate with collimator angle. The position of ion chamber, jaws, central axis are fixed to collimator angle. The signal measured to half blocked field 10x20 cm² for every 30° collimator angle. The beam spot calculated from signal measurement results. The ICS method uses two radiopaque rings with 8.5 cm diameter. Both of rings are placed at different heights of 64.5 cm and 150 cm SSD. Image acquired by varying both collimator and couch angle for every 30° and the beam spot position calculated by measuring the shift of rings centre. Measurement also performed using ball bearing test. Beam spot shift values from the CAOR using CPM and ICS measurements are closely similar, in the range of 0.05 – 0.65 mm and 0 – 0.53 mm respectively. The measurement using CPM and ICS methods can be used for routine quality assurance (QA) to ensure that the beam spot position still in tolerance.

1. Introductions
Quality Assurance (QA) of a Linear Accelerator (Linac) such as measurement of the beam spot position is an important part of patient safety. In a treatment planning system (TPS) the beam spot is assumed to be located on the central axis of the collimator at all gantry angles. The beam spot position should be on the central axis of rotation (CAOR), so the radiation isocenter size is minimal. However, there is the possibility for beam spot misalignment in use for a long time, so we need to check it regularly [1]. Beam spot position affects geometric and dosimetric properties of the beam, such as beam symmetry and flatness, the position and size of radiation isocenter [2].

Lutz et al have reported that the radiation field will shift laterally by the isocenter with gantry rotation if the beam spot position shift in cross plane [3]. The output factors of a small field can change drastically (greater than 10%) with position and shape of the beam spot [4]. Beam spot displacement can cause misregistration of image guidance system and blurring on portal imaging, so the image acquired becomes less sharp and image details become less visible [5]. Existing methods for measuring beam spot position are foil activation and beam spot cameras, these methods are quite difficult to implement and not suitable for routine QA measurement. Nyiri et al, measuring beam spot position uses two independent and accurate methods. The first method, the corotational penumbra modulation measurement, use an ionization chamber. The second method, the image center shift method, use Electronic Portal Imaging Device (EPID) and two opaque rods as objects [4]. Both of
those methods are self-referencing to the CAOR but require a specially made jig which is not suitable for quick measurement. In this study, we use the ionization chamber (IC) with novel phantom as IC holder and build up cap, and EPID images with two opaque rings as objects and also ball bearing. These methods is quite easy to perform compared with methods by Nyiri et al, so we can perform this QA regularly.

2. Methods
The measurement was conducted using linac Elekta Precise in Persahabatan Central Hospital. The beam spot position was measured using two methods. The first method was Corotational Penumbra Modulation (CPM) using ionization chamber and the second method was Image Center Shift (ICS) using Electronic Portal Imagining Device (EPID).

2.1. Corotational Penumbra Modulation (CPM)
The measurement used farmer ionization chamber with active area volume of 0.6 cc. The signal was measured for full beam of 20x20 cm² and half beam of 10x20 cm² with collimator angle rotated through 360° (180° to -180°) in step of 30° for 100 cm SAD, dose rate 600 MU/min and the MU given is 100 MU photon 6 MV. The curve of spatial sensitivity (signal change per 1 mm displacement of IC) is required to know the beam spot shift. The curve was obtained by measuring half beam of 10x20 cm² with collimator angle of 0°. The IC is adjusted so that the signal measured is 50 % of the full beam and the position of IC was then shift laterally to the right and left every 1 mm. The IC was parallel with the edge of half beam. The measurement setup can be seen in Figure 1.

![Figure 1. Measurement setup for corotational penumbra modulation method.](image)

2.2. Image Center Shift (ICS)
This measurement used EPID with two opaque rings as the objects. These two rings with same diameter of 8.5 cm were placed in different distances, the upper ring distance to the radiation source was 64.5 cm and the lower ring distance to the radiation source was 150 cm. The field size was 20x20 cm at isocenter and 10 MU of photon 6 MV were given to all collimator and couch table angle variations every 30°. The measurement setup can be seen in Figure 2. From the obtained images, the center of each circle was determined based on the profiles taken for cross-plane and in-plane orientation. These profiles were processed using Image J and the beam spot shift from CAOR was obtained based on the distance of the two circle centers.

Other than these two methods, ball bearing test was also conducted, which was performed by putting ball bearing with diameter of 5 mm at the distance of 64.5 cm from the radiation source and image acquisition was operated using EPID. The measurement used field of 10x10 cm² and given 10 MU with variations of collimator angles every 30° through 360°. The images were then processed...
using Image J by taking in-plane and cross-plane profiles, which then obtained the Full Width Half Maximum (FWHM) of each collimator angle variations.

3. Results
The measurement results used CPM method can be seen at Figure 3. All these measurements were conducted in counter clock-wise (CCW) collimator rotation with gantry 0° using 6 MV. The measured signal on half beam was ideally 50% of full beam’s signal, yet the measurement results displayed that the percentage ranged around 46 - 53%.

The values of beam spot’s shift from CAOR in each collimator angle rotation for CPM method can be seen in Table 1. The beam spot shifted around 0.02 – 0.57 mm, with 0.57 mm (σ = 0.40 cm) shift towards the collimator angle of 270° as the longest shift and 0.02 mm (σ = 0.21 cm) shift toward the collimator angle of 60° as the shortest shift. Negative value refers to the shifting towards half beam block’s edge. Senka et al (2003) reported that the beam spot of linear accelerator is not stationary and move up to 0.7 mm at the start of irradiation [5].

The measurement results using ICS method were displayed in Table 2. The different distance of two rings from radiation source position mean that if the beam spot is misaligned with the collimator axis, so their respective ring centres will project differently onto the EPID and gave the distance from two ring isocentres. The beam spot shift from CAOR was obtained for cross-plane and in-plane
orientation. The shifts of beam spot from CAOR for every 30° of collimator and couch table angles variations were less than 1 mm. The maximum shift was 0.53 mm at 240° collimator angle, 0° couch angle and cross plane orientation.

Table 1. Beam spot offset from CAOR with CPM Method.

| Collimator Angle (°) | Beam spot offset from CAOR (mm) | σ (mm) |
|----------------------|---------------------------------|--------|
| 0                    | -0.28                           | 0.08   |
| 30                   | 0.20                            | 0.04   |
| 60                   | 0.02                            | 0.21   |
| 90                   | -0.25                           | 0.12   |
| 120                  | -0.11                           | 0.12   |
| 150                  | -0.13                           | 0.23   |
| 180                  | -0.19                           | 0.01   |
| 210                  | -0.47                           | 0.02   |
| 240                  | -0.47                           | 0.26   |
| 270                  | -0.57                           | 0.40   |
| 300                  | -0.35                           | 0.11   |
| 330                  | -0.45                           | 0.21   |

Table 2. Beam spot offset from CAOR with ICS method for cross-plane and in-plane orientations.

| Collimator angle (°) | Couch angle (°) | Beam spot offset from CAOR (mm) |
|----------------------|-----------------|---------------------------------|
| 0                    | 0.00            | 0.00                            |
| 30                   | 0.18            | 0.00                            |
| 60                   | 0.44            | 0.09                            |
| 90                   | 0.44            | 0.33                            |
| 120                  | 0.13            | 0.36                            |
| 150                  | 0.27            | 0.43                            |
| 180                  | 0.18            | 0.18                            |
| 210                  | 0.18            | 0.43                            |
| 240                  | 0.53            | 0.09                            |
| 270                  | 0.09            | 0.18                            |
| 300                  | 0.27            | 0.00                            |
| 330                  | 0.27            | 0.44                            |
| 30                   | 0.36            | 0.12                            |
| 60                   | 0.27            | 0.18                            |
| 90                   | 0.09            | 0.27                            |
| 0                    | 0.27            | 0.44                            |

From Table 3, it can be seen that all FWHM values for every collimator angle variation towards cross-plane and in-plane orientations were almost identical. The average FWHM value for cross-plane
was 0.52 cm ($\sigma = 0.01$ cm) and for in-plane was 0.51 cm ($\sigma = 0.01$ cm). The results show that the images of ball bearing are symmetrical.

Table 3. FWHM of ball bearing for cross-plane and in-plane.

| Collimator Angle (°) | FWHM (cm) Cross-plane | FWHM (cm) In-plane |
|----------------------|------------------------|--------------------|
| 0                    | 0.50                   | 0.54               |
| 30                   | 0.51                   | 0.48               |
| 60                   | 0.52                   | 0.51               |
| 90                   | 0.54                   | 0.51               |
| 120                  | 0.54                   | 0.51               |
| 150                  | 0.52                   | 0.51               |
| 180                  | 0.51                   | 0.50               |
| 210                  | 0.53                   | 0.50               |
| 240                  | 0.53                   | 0.50               |
| 270                  | 0.52                   | 0.50               |
| 300                  | 0.52                   | 0.51               |
| 330                  | 0.51                   | 0.52               |

| Mean                 | 0.52                   | 0.51               |
| $\sigma$ (mm)        | 0.01                   | 0.01               |

4. Discussions

The size and shape of beam spot can differ from one machine to another and even in same machine with different energies for 6 – 25 MV [6], in this study we use 6 MV energy. The two methods used in this study are the quantitative methods for measuring beam spot position. All measurements were conducted at gantry angle of 0° and there should be no significant differences in the measurement results for other gantry angles [11]. The CPM method assumes that spatial sensitivity (signal/mm) is independent of the collimator angle, and this gives uncertainty in the calculation of beam spot position. In the CPM method, the detector choice is important. The smaller the detector the greater the sensitivity, so the detector with small active volume is better for this measurement. Signal readings will be the same if the beam spot is located at CAOR. From Figure 3, the minimum and maximum signal were 46% and 53% at 270° and 30° collimator angle respectively and maximum beam spot offset was 0.57 mm ± 0.40 mm.

In ICS method, beam spot displacement calculated using the equation (1) given by Nyiri et al.

$$d = \frac{(d_3 - d_1)}{h_2 h_1}$$  (1)

where $d_3$ and $d_1$ are the projected center of upper and lower rings, respectively, $h_2$ is the distance from the radiation source to the upper ring, $h_1$ is the distance from the radiation source to the lower ring, and $H$ is the distance from the radiation source to the EPID [4]. In this method we delivered 10 MU to each image acquisition, Slama et al (2019), reported that the beam spot was shown to be unstable for the first 1-3 s, or 10-30 MU for dose rate 600 MU/min, before stabilizing to within 0.01 mm from the mean position for the Varian Trilogy and Varian Clinac iX linacs [11]. Beam spot position for ICS method with collimator and couch angle variation can be seen in Table 2. All the beam spot offset less than 1 mm with maximum displacement was 0.53 mm.

Both measurement with CPM and ICS methods gave the almost identical value of the beam spot shift and all values still within tolerance (the tolerance value is 1 mm) [5]. If the shift more than 1 mm, beams measured as failure and restrictive from clinical use until the beam spot is steered back to its optimal position. Meanwhile, American Association of Physics in Medicine (AAPM) report the tolerance was 2 mm (AAPM report no 13 1984) [9]. Riis at al (2018) reported that for the target
perfectly centered on the collimator axis, the maximum allowed of the beam spot motion is 1.7 cm, the tolerances should be reconsidered and related to the treatments and equipment used today and the value different for stereotactic, VMAT, IMRT and 3DCRT technique [8]. AAPM Task Group 142 recommends that maximum runout of each axis (size of isocenter) and the coincidence of radiation and mechanical isocenter should be no more than 1 mm for stereotactic radiosurgery (SRS) or stereotactic body radiotherapy (SBRT), and no more than 2 mm for non SRS treatment machines [10].

Ball bearing measurement is to determine the symmetry of the ball bearing image with various collimator angle. The mean FWHM for cross-plane was 0.52 cm (σ = 0.01 cm) and in-plane was 0.51 cm (σ = 0.01 cm). Each FWHM measurement of ball bearing is almost the same, it shows that the image of the ball bearing tends to symmetry or circular shape and indicated that the beam spot is centered on the CAOR. This result differ from the study by Munro et al. (1988), they found that the shape of x-ray source are mostly elliptical and the long axis is perpendicular to the gantry axis [6]. Herwiningsih et al. (2015), reported that elliptical shaped beam spot gave a better penumbra matching with the measurement data in both in-line and cross-line direction rather than a circular shape beam spot in Elekta Axesse linac model. Different linac machines will have their optimum value of the radiation source [7].

All methods shown that beam spot position is relatively stable because the beam spot measurements in this study were carried out in linac that were routinely maintenance. That mean all techniques in this study can be implemented as a practical and reliable method of measuring beam spot shift.

5. Conclusions
This work illustrated that beam spot shift values from the CAOR using CPM and ICS measurements were closely similar, in the range of 0.05 – 0.65 mm and 0 – 0.53 mm respectively. These two results showed that this linac beam spot is in good condition, the shifts of beam spot are less than 1 mm and match with all recommendation [4, 8, 9, 10]. The measurement using CPM and ICS methods can be used for routine QA to ensure that the beam spot position is still within tolerance.

References
[1] Chojnowski J M, Barnes M P, Sykes J R and Thwaites D I. Beam focal spot position: The forgotten linac QA parameter. An EPID-based phantomless method for routine stereotactic linac QA. J Appl Clin Med Phys 2017 Sep;18(5):178-183.
[2] Chojnowski J M, Taylor L M, Sykes J R and Thwaites D I. Beam focal spot position determination with the agility® head; practical guide with a ready-to-go procedure. J Appl Clin Med Phys 2018 Jul;19(4):44-47.
[3] Lutz W R, Larson R D, and Bjarnargard B E. Beam alignment test for therapy accelerators. Int. J. Radiat. Oncol., Biol., Phys. 7, 1727–1731 (1981).
[4] Nyiri B J, Smale J R, and Gerig L H. Two self-referencing methods for the measurement of beam spot position. Med Phys, 2012 Dec;39(12):7635–7643.
[5] Sonke J J, Brand B, van Herk M. Focal spot motion of linear accelerators and its effect on portal image analysis. Med Phys 2003 Jun;30(6):1067-75.
[6] Munro P, Rawlinson J A, and Fenster A. Therapy imaging: Source sizes of radiotherapy beams. Med Phys 1988 Jul/Aug; 15(4):517-524.
[7] Herwiningsih S and Fielding A. Focal spot estimation of an Elekta dedicated stereotactic linear accelerator Monte Carlo model. J Phys Conf Ser 694 (2016) 012013.
[8] Ris H L, Ebert M A, and Rowshanfazad P. Detection of the focal spot motion relative to the collimator axis of a linear accelerator under gantry rotation. Phys Med Biol 2018.
[9] AAPM report no. 13 1984. Physics aspects of quality assurance in radiation therapy American Institute of Physics.
[10] Klein E E, et al. Task Group 142 report: Quality assurance of medical accelerators. Med Phys 2009;36(9):4197-212.
[11] Slama L A, et al. Beam focal spot intrafraction motion and gantry angle dependence: A study of Varian linac focal spot alignment. Physica Medica 63 (2019) 41-47.