An in-house software program for quantitative image quality evaluation of linac cone-beam CT system

Kasmayanti Sakaria, S Y Lim, Hafiz M Zin

Advanced Medical and Dental Institute, Universiti Sains Malaysia, Bertam, 13200 Kepala Batas, Pulau Pinang, Malaysia

Email: hafiz.zin@usm.my

Abstract. The study presents application of an in-house software program to calculate image quality parameters of kV cone-beam CT (CBCT) system in radiotherapy. The parameters include uniformity, noise, contrast-to-noise ratio, CT number linearity, spatial resolution and geometric distortion as recommended in AAPM TG142 and TG179 quality assurance (QA) programme for image quality performance of kV CBCT. The computer algorithm packaged in the software program is developed using MATLAB (MathWorks, Natick, MA). The algorithm was optimised for two CT image quality phantoms, Catphan 600 (The Phantom Laboratory, Salem, NY) and CIRS 062QA (CIRS, Norfolk, VA). The phantoms were scanned with XVI CBCT system (Elekta AB, Stockholm, Sweden) using an optimised CT imaging protocol. The algorithm measures the image quality metrics from the corresponding image quality test patterns in the reconstructed CT images. The algorithm provides image quality parameters from both phantoms quantitatively. The software program allows the results to be exported and recorded in MS Excel for monitoring the performance trend of the image quality parameters. The software reduces measurement uncertainties from qualitative human observation of the test patterns.

1. Introduction

Kilovoltage (kV) cone-beam computed tomography (CBCT) system provides 3D volumetric images of good contrast between soft tissues and bony structures at low radiation dose for image guided radiotherapy. The scanned image is registered with the CT reference image obtained during radiotherapy simulation for tumour localisation and patient positioning verification prior to radiotherapy treatment [1,2]. Poor image quality will affect the accuracy in the image registration, thus lead to inaccurate treatment delivery [3].

The kV CBCT system imaging performance requires periodic inspection to ensure the accuracy the image guided radiotherapy system. The image quality assessment method is highly observer-dependent and may introduce interobserver and the intraobserver variation. This study presents a newly developed in-house software for assessing the imaging performance of kV CBCT system quantitatively and automatically. The image quality analysis algorithms were developed using MATLAB (MathWorks, MA, USA). The image quality parameters evaluated include image noise, image uniformity, contrast-to-noise ratio (CNR), CT number linearity, spatial resolution and geometric distortion as recommended in AAPM TG142 [4] and TG179 [5]. The algorithms were packaged into a software program with graphical user interface (GUI).
2. Materials and methods

2.1. kV CBCT system
The kV CBCT system consists of an x-ray source tube and an amorphous silicon (aSi) flat-panel imager, mounted orthogonally to the gantry head (Elekta AB, Stockholm, Sweden). The size of the flat-panel imager is 41 × 41 cm² and consists of 1024 × 1024 pixels with 16-bit depth. The imaging parameters used for the scanning were 120 kVp tube voltage and a tube current of 0.4 mAs per projection.

2.2. Image Quality Phantoms
The image quality phantoms used in this study were Catphan 600 (The Phantom Laboratory, Salem, NY) and CIRS 062QA (CIRS, Norfolk, VA). The Catphan 600 has a diameter of 20 cm and a length of 19.5 cm. It comprises of five test modules: CT linearity, beads geometric, high-contrast spatial resolution, low contrast spatial resolution and uniformity. Whereas, the CIRS 062QA has a diameter of 18 cm and a length of 10 cm. It consists of four test modules including spatial resolution, CT number linearity, low contrast and uniformity. The phantom was suspended at the end of the treatment couch and aligned using room laser. A series of approximately 660 projection images were captured at 360° of gantry angle rotation with a frame rate of 5.5 frames/second. The scanned images were reconstructed using Feldkamp 3D back-projection reconstruction algorithms.

2.3. Algorithm
The in-house software performed automated evaluations of the image noise, uniformity, CNR, CT number, spatial resolution and geometric distortion. Details of the algorithm were presented in our previous work [6]. The software GUI simplifies the image quality evaluations by providing an interface to set the region of interests (ROIs) on the CT slice image with the test pattern that corresponds to the parameters evaluated. The software will automatically perform the calculation and the results are displayed on the software interface. The software also allows all the results to be exported and recorded in MS Excel for monitoring the performance trend of the image quality parameters.

2.3.1. Noise and uniformity. Image noise and uniformity were determined from the uniformity test module in both phantoms. Figure 1 shows a screen capture of the software GUI for the noise, integral non-uniformity (INU) and uniformity index (UI) evaluations of Catphan 600. Image noise was assessed by selecting ROI with a length of 10 mm and the width covered 60% of the phantom size at horizontal and vertical directions. The measured pixel value and best fit pixel value with a polynomial function of second degree were displayed in the GUI to see the variations of the signal received by the detector. The amount of noise was determined from the standard deviation of the residual between best fit and measured pixel values of each ROI [7]. INU was determined from the ROIs for noise evaluation. The average pixel values, \( \bar{x} \) across each ROI were used to calculate the INU by dividing the difference between maximum and minimum \( \bar{x} \) with the sum of the two values. UI was assessed by evaluating the degree of cupping and capping artefact. Five ROIs of size 10 mm × 10 mm were selected that are located one at the centre and another four peripheries at 45 mm away from the centre of the phantom. UI was defined by the highest percentage difference between central and peripheral ROIs [8,9]. The positive and negative value of UI indicates the presence of cupping and capping artefacts in the reconstructed image.

2.3.2. CNR and CT number linearity. CT number linearity test module from both phantoms were used to assess CNR value and CT number linearity. Figure 2 shows the GUI for the CNR and CT number linearity evaluations of CIRS 062QA. A ROI of size 6 mm × 6 mm from every insert and the background was selected. CNR was defined as the difference of average pixel values between the inserts and background over the average noise [10]. Meanwhile, CT number was determined for all inserts by using formula introduced by Krizz and Strauss [9]. The CT number of all inserts presented on the GUI are
shown in Figure 2. The software also provides the calculation of correlation coefficient, R between theoretical CT number [10] and measured CT number.

**Figure 1.** GUI for the evaluation of image noise and uniformity of Catphan 600.

**Figure 2.** GUI for the evaluation of CNR and CT number linearity of CIRS 062QA.
2.3.3. Spatial resolution. Test module of high-contrast spatial resolution from Catphan 600 and spatial resolution from CIRS 062QA were used to evaluate the level of spatial resolution of the image. Figure 3 shows a screen capture of the software GUI for the spatial resolution evaluations of CIRS 062QA. The spatial resolution was evaluated using the modulation transfer function (MTF). The MTF value computed from the line-pair bar regions in the test module by using Droge and Morin approach [11]. The MTF curve is plotted in the interface and the spatial frequency at relative MTF (RMTF) of 50%, $f_{0.5}$ and 10%, $f_{0.1}$ were determined [12].

![Figure 3. Interface of the software for the evaluation of spatial resolution of CIRS 062QA.](image)

2.3.4. Geometric distortion. The geometric distortion was determined by measuring the distance between two objects of known distance. This were obtained from the CT number linearity and the low contrast test module of Catphan 600 and CIRS 062QA, respectively. CT number linearity test module of Catphan 600 consists of four points which are positioned 50 mm apart. While, low contrast test module of CIRS 062QA consists of three points arranged in an equilateral triangle of 55 mm apart. A ROI was selected for each pair of points. The intensity profiles across the selected ROIs were plotted. Based on the profiles, distance between the two points were determined and compared with the actual distance as shown in Figure 4.

3. Results and discussion
The imaging performance of kV CBCT system was evaluated using the in-house developed software for 6 month-period. The results are summarised in Table 1. The discrepancies between the two phantoms are due to the difference in the size and the geometric design of the phantoms as described in the previous study by Lim et al. [6]. In general, the results of image quality of kV CBCT system met the manufacturer’s specifications and the range obtained by the previous researchers such as Letourneau et al., Bissonnette et al., Gulliksrud et al. and Yin et al. [7,8,13,14].
Figure 4. GUI for the evaluation of geometric distortion of Catphan 600.

Table 1. The results of image quality evaluated using in-house developed software for 6 months.

|                         | Catphan 600 (Mean ± STD) | CIRS 062QA (Mean ± STD) | Manufacturer’s specification and measurements obtained from the previous researchers |
|-------------------------|--------------------------|--------------------------|-----------------------------------------------------------------------------------|
| Noise                   |                          |                          |                                                                                   |
| Horizontal              | 4.9 ± 0.20               | 4.6 ± 0.32               | Larger phantom noisier than the smaller sized phantom [7]                         |
| Vertical                | 4.9 ± 0.23               | 4.7 ± 0.40               |                                                                                   |
| Uniformity              |                          |                          |                                                                                   |
| INU horizontal          | 0.01 ± 0.001             | 0.03 ± 0.003             | 0.009 to 0.039 [8]                                                                |
| INU vertical            | 0.02 ± 0.002             | 0.03 ± 0.004             |                                                                                   |
| UI                      | -0.4 ± 0.14              | 1.9 ± 0.24               | -8.9 to 4.5 [8]                                                                  |
| CNR                     |                          |                          |                                                                                   |
| Air                     | 68.4 ± 8.11              | 113.2 ± 15.93            |                                                                                   |
| LDPE                    | 11.2 ± 0.95              | 10.4 ± 1.42              |                                                                                   |
| Polystyrene             | 6.9 ± 0.97               | 5.6 ± 0.82               | Comparable with the results obtained by Stock et al. [9]                         |
| Acrylic                 | 2.0 ± 0.50               | 7.4 ± 0.69               |                                                                                   |
| Delrin                  | 13.9 ± 1.77              | 25.1 ± 2.59              |                                                                                   |
| Teflon                  | 44.8 ± 9.08              | 70.6 ± 5.30              |                                                                                   |
| CT Number               |                          |                          |                                                                                   |
| Air                     | -1005.7 ± 2.60           | -1001.7 ± 0.86           | -1018.3 to -1008.0                                                               |
| LDPE                    | -102.5 ± 3.65            | -105.0 ± 3.37            | -95.7 to -92.3                                                                   |
| Polystyrene             | -44.7 ± 2.56             | -47.2 ± 2.90             | -36.0 to -32.0                                                                   |
| Acrylic                 | 124.2 ± 3.55             | 113.6 ± 3.62             | 124.3 to 126.3                                                                  |
| Delrin                  | 350.9 ± 5.75             | 350.5 ± 6.37             | 353.3 to 354.7                                                                  |
| Teflon                  | 963.0 ± 10.57            | 970.9 ± 8.59             | 973.0 to 979.7                                                                  |
| Spatial resolution      |                          |                          |                                                                                   |
| $f_{x0}$                | 4.0 ± 0.19               | 3.1 ± 0.17               | 2.7 to 5.2 lp/cm                                                                 |
| $f_{x1}$                | 6.9 ± 0.6                | 5.5 ± 0.41               | 4.6 to 9.9 lp/cm                                                                 |
| Geometric distortion    |                          |                          |                                                                                   |
| Horizontal              | 0.0 ± 0.29               | 0.0 ± 0.0                | ± 1 mm [14]                                                                      |
| Vertical                | 0.3 ± 0.38               | -0.1 ± 0.45              |                                                                                   |
| Angle 225°              | -                        | 0.0 ± 0.29               |                                                                                   |
4. Conclusions
An in-house software program provides automated and quantitative evaluations of the image quality parameters of kV CBCT image guidance system. The software may reduce uncertainties from qualitative human observation of the test patterns. The automated measurement can be performed more frequently than monthly as it requires less time hence raise the confidence of the use kV CBCT system as an imaging tool for accurate treatment delivery.

References
[1] Stützel J, Oelfke U, and Nill S 2008 A quantitative image quality comparison of four different image guided radiotherapy devices Radiother Oncol. 86 20–4.
[2] Zamri NAM, and Zin HM 2017 Setup uncertainty of head and neck cancer (HNC) patients treated with Image Guided and Intensity Modulated Radiotherapy (IG-IMRT) J Med Phys Biophys. 4 108–14.
[3] Garayoa J, and Castro Pablo C 2013 A study on image quality provided by a kilovoltage cone beam computed tomography J Appl Clin Med Phys. 14 239–57.
[4] Klein EE, Hanley J, Bayouth J, Yin F-F, Simon W, Dresser S, et al. 2009 Task Group 142 report: Quality assurance of medical accelerators Med Phys. 36 4197.
[5] Bissonnette J-P, Balter P a, Dong L, Langen KM, Lovelock DM, Miften M, et al. 2012 TG-179 Quality assurance for image-guided radiation therapy utilizing CT-based technologies Med Phys. 39 1946–63.
[6] Lim SY, and Zin HM 2017 Quantitative image quality evaluation for kV cone-beam CT-based IGRT J Phys Conf Ser. 851 12029.
[7] Létourneau D, Wong JW, Oldham M, Gulam M, Watt L, Jaffray DA, et al. 2005 Cone-beam CT guided radiation therapy: Technical implementation Radiother Oncol. 75 279–86.
[8] Bissonnette J-P, Moseley DJ, and Jaffray DA 2008 A quality assurance program for image quality of cone-beam CT guidance in radiation therapy Med Phys. 35 1807–15.
[9] Stock M, Pasler M, Birkfellner W, Homolka P, Poetter R, and Georg D 2009 Image quality and stability of image-guided radiotherapy (IGRT) devices: A comparative study Radiother Oncol. 93 1–7.
[10] Elstrom U V., Muren LP, Petersen JBB, and Grau C 2011 Evaluation of image quality for different kV cone-beam CT acquisition and reconstruction methods in the head and neck region Acta Oncol (Madr). 50 908–17.
[11] Droege RT, and Morin RL 1982 A practical method to measure the MTF of CT scanners Med Phys. 9 758–60.
[12] de las Heras Gala H, Torresin A, Dasu A, Rampado O, Delis H, Hernández Girón I, et al. 2017 Quality control in cone-beam computed tomography (CBCT) EFOMP-ESTRO-IAEA protocol (summary report) Phys Medica. 39 67–72.
[13] Gulliksrud K, Stokke C, and Trægde Martinsen AC 2014 How to measure CT image quality: Variations in CT-numbers, uniformity and low contrast resolution for a CT quality assurance phantom Phys Medica. 30 521–6.
[14] Yin F-F, Wong J, Balter J, Benedict S, Bissonnette J-P, Craig T, et al. 2009 The Role of In Room kV X-Ray Imaging for Patient Setup and Target Localization Report of AAPM Task Group 104 American Association of Physicists in Medicine. 2009.