MANSOURA JOURNAL OF Physics
Official Journal of Faculty of Science, Mansoura University, Egypt
E-mail: scimag@mans.edu.eg ISSN: 2974-4954

Evaluation of Acceptance Testing Performance for CT Simulator

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Received: 24/ 8 /2022
Accepted: 11/10 /2022

Abstract: Objective: This study aimed to carry out the acceptance testing for a newly installed CT simulator at Clinical Oncology & Nuclear Medicine department, Mansoura University Hospital, Mansoura, Egypt, and examined its clinical use. The manufacturer's quality phantom was scanned by the standard scanning protocol, with a tube voltage of 120 kV and 213 mA, in addition to the dual-energy protocol of 80 kV and 140 kV. Image quality such as the Hounsfield unit (HU) values, image noise, image uniformity, presence of artifact, spatial resolution, and slice thicknesses was also examined. The accuracy of the position of the electromechanical component was evaluated. Also, the computed tomography dose index (CTDI) values were investigated.

Results: The results showed that the mean value of the CT number was 1.03 HU at 80 kV, and at 120 kV the mean value was 1.09 HU, whereas at140 kV the mean value was 1.1 HU. The noise level was measured for each ROI in all images of the water section for the body mode scanning and was 11.52, 11.07, and 10.5 at 80, 120, and 140 kV, respectively. The mean uniformity of the CT image was calculated by calculating the maximum difference values between the mean HUs of each ROI which were 0.89, 0.95, and 0.98 HU at 80, 120, and 140 kV, respectively. The Gantry lasers were orthogonal and parallel with the scan plane, moreover, wall lasers were orthogonal and parallel with the scan plane and intersect with the scan plane center, and the laser overhead was orthogonal to the imaging plane. The couch position accuracy was tested using the QA laser phantom. Also, the tabletop scanning at the zero position showed that the tabletop doesn't contain any artifact-producing materials. The gantry index showed accurate results on the ready-pack film so, the test was accepted. The gantry tilting test was passed where the angles of tilting on the ready-pack film were equal to the tilted angles. The measured values of CTDI were 21.54, 29.31, 24.18, 21.98, and 26.03 mGy for the center, 12 o'clock, 3 o'clock, 6 o'clock, and 9 o'clock positions, respectively.

Conclusions: The new CT simulator showed comparable results and is acceptable and suitable for clinical use.

Keywords: Acceptance tests; CT simulator; Image quality; CT dose index.

1.Introduction

Since the evolution of the first Computed Tomography (CT) scanner in the 1970s by Godfrey Newbold Hounsfield and Allan M. Cormack, the CT has been used for diagnosis and in radiotherapy planning purposes due to its accuracy in creating cross-sectional images of high radiographic contrast [1]. The radiotherapy process is very sensitive and undergoes many phases one known as radiation treatment planning consists of steps that include diagnosis of the patient, tumor delineation, image acquisition for treatment planning, and dose calculation. In radiotherapy, it is essential for the patient to be scanned in the position that will be applied during the radiotherapy sessions. This was a problem because of the difference between the patient's position on CT and during delivery of the treatment fractions, therefore the CT simulator was designed because the CT was not accurate enough for the radiotherapy process. The main differences between CT and CT simulators are that the CT simulator has: 1) the flat tabletop to ensure that the position of the patient during scanning is the same as during delivery of the treatment fractions, 2) the external laser with opaque markers to place markers on the patient skin, 3) the software which allows treatment planning and virtual simulation of the therapeutic beam shape. Also, there is an important difference between CT and CT simulators: the large gantry bore size which facilitates immobilization devices usage during scanning to ensure that the patient is fixed allover the scan, also afford to scan large patients and make it comfortable [2, 3]. For an accurate CT simulation process, the CT machine should obtain an image with high quality and resolution with minimal patient radiation dose. According to the American Association of Physicists in Medicine (AAPM), submission of clinical use, dose measurements, and scanning protocols are essential for any facility that uses a CT device [4, 5]. Recently, a CT simulator was newly installed in the Clinical Oncology and Nuclear Medicine department at Mansoura University Hospital, Mansoura, Egypt. Therefore, this study was aimed to ensure its acceptance for use in radiotherapy and diagnosis processes. The main acceptance tests include 1) image quality parameters as CT number, noise level, uniformity level, modulation transfer function (MTF), and slice thickness, 2) performance of electromechanical components 3) CT dose index (CTDI), and radiation safety measurements [6-9].

2. Materials and methods

A SEIMNES (SOMATOM Confidence 64-slice) CT simulator was newly installed in the Clinical Oncology and Nuclear Medicine department at Mansoura University Hospital. The image quality tests were performed using the manufacturer quality phantom. A humanoid Alderson-Rando phantom, quality assurance (QA) laser device, long ruler, ready-pack films, and spirit level were used for testing the performance of electromechanical components. UNIDOS electrometer with a pencil ion chamber and CTDI head phantom were used in CTDI measurements. A survey meter was used for radiation exposure measurements. The accreditation tests were carried out according to the AAPM during the acceptance testing process of the CT simulator.

2.1. Image quality evaluation

The assessment of the image quality for the CT simulator was done in terms of image quality tests such as CT number or HU, noise level, uniformity level, spatial resolution (MTF), and slice thickness. The manufacturer's quality phantom, which represented the water module, the slice thickness module, and the wire and ball module was used. The quality phantom was scanned with the standard 120 kV and the dual-energy, 80 kV and 140 kV, mAs = 213, WW= 100 HU, WL= 0, and slice thickness = 5 mm [10]. To perform data analysis image j software version 22 (National Institute of Health, USA, (ImageJ nih.gov)) was used as reported before [10].

Hounsfield units (HU)

The CT number is defined as the number of photons in the region of interest (ROI). Scanning of the water section of the quality phantom was done to obtain reconstructed images. The CT numbers are calculated during image reconstruction using the following relationship:

$$\text{CT number (HU)} = \frac{\mu_m - \mu_w}{\mu_w} \times 1000$$

where μ_m and μ_w are the linear attenuation coefficients for a scanned tissue and water for a given pixel as displayed in figure 1. The CT numbers for all five ROIs must be within ± 4 HU [11, 12].

Noise level

The image noise may express as the standard deviation in the ROI, using the water section in the manufacturer's phantom, image noise was calculated as the average value of the measured differences of HUs in five equal ROIs [4].

Image uniformity

The uniformity of the image can be evaluated by measuring the minimum and the maximum value of CT number in the ROI of ~1.0 cm^2 in the center of the image of the uniform water section and at four positions at the periphery then calculating uniformity (U) from the equation: [13].

$$U = 1 - \frac{\text{Max pixel count - Min pixel count}}{\text{Max pixel count + Min pixel count}}$$

Where Max pixel count and Min pixel count are defined as the maximum and minimum pixel count within a ROI.

Image artifacts

Artifacts mean any pattern visible in the image that is not part of the object being imaged. Although, the importance of the image artifacts test, there are no phantoms generally available that are dedicated to assessing the artifacts. The presence of artifacts can be assessed subjectively throughout an acceptance test [16].

Slice thickness

The thickness of the tomographic section is tested by measuring the thickness of the inclined aluminum ramp of the tomographic section as shown in figure 2. The width is defined as the Full Width at Half Maximum (FWHM) of the CT values profile. The measurement is performed for every collimator opening, each with the maximum number of slices reconstructed [15].

Spatial resolution

The resolution of the image is estimated by evaluating the image of a thin tungsten wire placed in a rod of plastic and centered in the scan plane. The MTF is calculated as the Fourier Transformations of the point spread function as represented in figure 3. The 10% MTF and 50% MTF values were evaluated [5, 14].

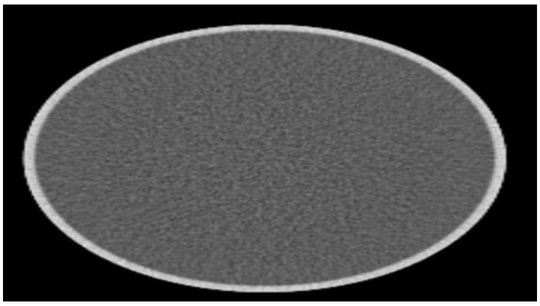

Figure (1) CT image for the homogenous water part of the CT manufacturer's quality phantom

2.1. Performance of electromechanical components

a) Lasers system testing

The three separated components of the light laser in the CT simulator are the gantry lasers, the wall-mounted lasers, and the sagittal laser. The alignment accuracy of the three components is a prerequisite for accurate localization of the patient and definition of his anatomy [10, 17].

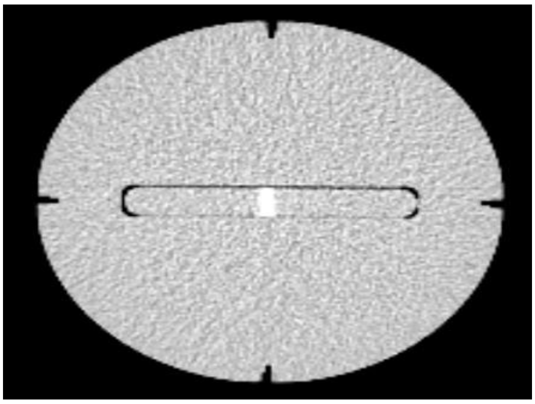

Figure (2) CT image of an aluminum ramp at the intersection of the quality phantom

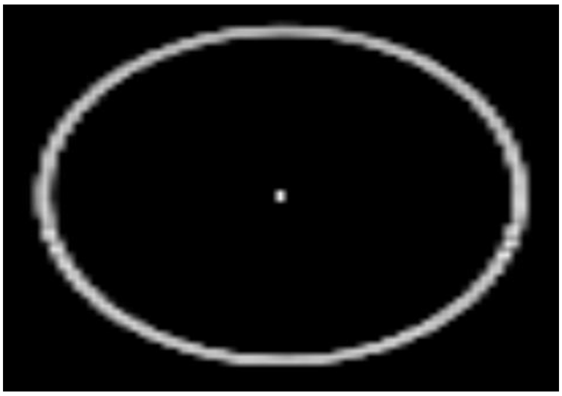

Figure (3) CT image of a thin tungsten wire used to calculate MTF.

1.**Gantry lasers are precisionally identified to the scan plane within the gantry opening**

Horizontal and vertical internal lasers of the gantry are aligned with the horizontal and vertical holes of the laser QA device, respectively. The well-viewed pegs of the QA device are an indication that the lasers of the gantry are precisionally fixed with the scan plane as shown in figure 4 [5, 17].

1.Gantry lasers are parallel and perpendicular with the imaging plane

By aligning the vertical gantry laser with the center hole of the QA device, the lasers should connect the pegs of the laser device to the full couch travel. The cursor option on the CT simulator scanner is used to verify if the gantry lasers are fixed in the center of the plane or not, as shown in figure 4 [17].

1.Vertical side-wall lasers are precisionally spaced from the isocenter of the scan plane

The QA device in this test is attached to the gantry lasers and the couch is raised and lowered vertically. Using the longitudinal table indicator, the table is moved away from the gantry at a distance equal to the distance separated by the gantry and the lasers. After the movement, both wall lasers must enter the two side holes of the QA device. If the lasers do not enter the holes accurately, this showed that the lasers are not precisionally aligned or that the couch motion is not accurately defined [5].

1.Wall lasers are attached at the isocenter of the scan plane

The laser device is aligned with the external wall lasers and the couch is moved vertically and horizontally. The lasers should be intersected the pegs of the QA device the full time of the test [5].

1.The sagittal laser is perpendicular to the plane

In this test, the QA laser device is aligned with the sagittal laser and the table is attracted away and towards the gantry. The intersection of the lasers to the holes of the QA device indicates that the lasers are perpendicular to the scan plane and that the couch travel is correct [5].

b) Couch and tabletop testing

1.The tabletop is perpendicular to the scan plane

To assure that the tabletop is perpendicular to the scan plane, the QA device is fixed at the head of the tabletop, then the device is aligned by the gantry lasers and an image of the device was obtained. The QA phantom is then put at the foot of the table and a single image is obtained. The position of the center holes on both images, measured using the scanner cursor tool, should be superimposed [10].

1.Table vertical and longitudinal motions are accurate and reproducible

The accuracy and reproducibility of the vertical motion of the table are evaluated by putting a ruler vertically on the couch and observing the laser position during raising and lowering the table. The longitudinal movement can be also checked by putting a long ruler longitudinally on the couch top and attracting the table in and out of the gantry. The laser position must be tolerated within ±2 mm [5].

1.Table index and position under scan plane are accurate

A ready-pack film is placed on the couch top and exposed to radiation twice at a fixed space with a small slice thickness as represented in figure 5. The lines obtained from the scans must be superimposed and the space between lines on the film should equal the thickness used for the scan [5].

1.The tabletop does not contain any artifact-producing objects

For accurate image acquisition, the fat tabletop should not contain any objects that cause image artifacts. The table is scanned in zero position to ensure that it does not contain any artifact-producing objects as displayed in figure 6 [10].

c) Gantry tilt

1.The gantry precisionally returns to the vertical position after tilting

The QA device is positioned with the laser of the gantry and the gantry is tilted to the right and the left direction then back to the zero position. The alignment of the QA phantom with the lasers of the gantry should be within ±1 mm [16, 18].

2.The gantry tilt angle with the nominal vertical position is accurate

A ready-pack film is placed on a water equivalent quality assurance device and centered on the tabletop then attached with the gantry lasers. A single scan with a 1 mm slice thickness can be evaluated, where the gantry is at zero position. The gantry is then tilted to the superior and inferior directions and a single scan is obtained in the two cases. The angles between the three axial exposures in the three positions should be within ± 1° [5].

2.1.CTDI measurements

CTDI measurement is performed using a pencil ionization chamber (100 mm length) with the CTDI head phantom. The ionization chamber is centered in the axial direction in the system axis, figure 8. The slice plane has to run through the center of the ion chamber. An appropriate dosimeter is connected to the ionization chamber. The CTDI weighted ($CTDI_w$) represents the dose from one axial CT scan

Where:

$$CTDI_w = \frac{CTDI_{center} + 2\ CTDI_{periphery}}{3}, \text{ and}$$

$CTDI_{vol}$ is the average dose over the x, y, and z directions, then $CTDI_{vol}$ can be expressed as:

$$CTDI_{vol} = \frac{CTDI_w}{pitch}$$

Dose Length Product (DLP) (mGy.cm) = $CTDI_{vol}$(mGy) × scan length(cm) [10].

Statistics

The data of our results were evaluated using SPSS version 22 (SPSS Inc., Chicago, IL, USA).

In order to subjective estimation, the T-test was used to resolve variations within the tabulated and obtained results.

The p-value was calculated with SPSS version 22. A p-value that is less than 0.05 was considered to be accepted as a statistically significant level.

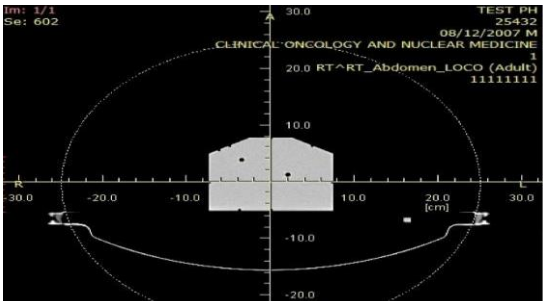

Figure (4) CT image of the quality assurance laser phantom.

Figure (5) Irradiated ready-pack film**.**

Figure (6) CT image of the flattabletop at zero position

Figure (7) Irradiated ready-pack film.

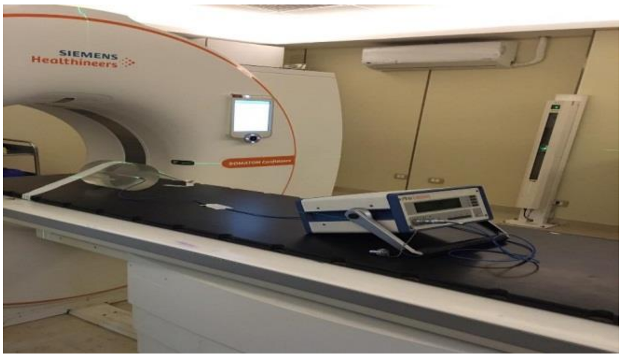

Figure (8) CTDI head phantom and the electrometer

3.Results and discussion

3.1. Image quality

For the CT number measurements, the uniform water part of the manufacturer's phantom was scanned with the two scanning techniques, the standard (120 kV) and the dual-energy (80 and 140 kV), to obtain CT images as shown in figure 1. The CT number of water was measured for each image and tabulated in table 1. The mean CT values were 1.03, 1.09, and 1.1 at 80, 120, and 140 kV, respectively. The CT number of water should be between -5 HU and 5 HU. The CT numbers for all ROIs were in the acceptable range so, the CT number test was accepted.

Table 1: CT number measurements

	kV				
	80	**120**	**140**	**Student t-test**	**p-value**
Mean ± SD	1.03 ± 0.19	1.09 ± 0.15	1.1 ± 0.38		0.01
Min - Max	0.88–1.33	0.32 – 1.99	0.74 – 1.72	128	

Table 2: Image noise values.

	kV				
	80	**120**	**140**	**Student t-test**	**p-value**
Mean ± SD	11.52 ±1.27	11.07 ± 1.25	10.5 ± 1.24	2.91	0.039
Min - Max	10.45-13.79	10.08 – 12.9	9.86 – 13.96		

The noise level was measured for each ROI in all images of the water section for the body mode scanning as in table 2. The noise values were 11.52, 11.07, and 10.5 at 80, 120, and 140 kV respectively. The noise values should be less than 12 HU as reported by the AAPM [10]. All values were in the acceptable range therefore, the test was accepted.

The mean uniformity of the CT image was calculated by calculating the maximum difference value between the mean HUs of each ROI and tabulated in table 3. The mean values were 0.89, 0.95, and 0.98 at 80, 120, and 140 kV, respectively. The mean uniformity should be between - 4 and 4. All uniformity measured values were in the accepted range therefore, the test was accepted.

The SNR values were measured and tabulated in table 4. The mean SNR values were 0.09, 0.098, and 0.1 at 80, 120, and 140 kV, respectively. All resulting measurements were in the accepted range compared with the tolerance values of the AAPM [5].

The high contrast resolution was determined by evaluating the point spread function also, and the MTF was measured as the Fourier Transformation (FT) of the point spread function. The 10% and 50% MTF were evaluated and were 5.65, 5.7, 5.91 and 3.22, 3.32, 3.4 at 80, 120, and 140 kV respectively. Table 5 indicates the measured values of MTF. As it appears for all sets of scan parameters MTF10 and MTF50 showed acceptable results.

The slice thickness measurements were illustrated in table 6. The scan parameters of slice thicknesses tests were 213 mA, and 120 mm field of view for the standard 120 kV and the dual-energy (80 and 140 kV). The measured values of the slice thickness were 1.65, 1.47, and 1.41 at 80, 120, and 140 kV, respectively at 1.5 mm reconstructed slice width. Whereas they were 5.44, 5.4, and 5.32 at 80, 120, and 140 kV, respectively at 5 mm slice width reconstructed. The slice thickness measured should be accurate within ±1 mm. All tests indicate that the slice thickness determinations were accepted as mentioned by the AAPM report [5].

Table 3: Image uniformity measurements

	kV				
	80	**120**	**140**	**Student t-test**	**p-value**
Mean ± SD	0.89± 0.022	0.95 ± 0.023	0.98 ± 0.028	24.24	
Min - Max	0.72–0.96	0.79 – 0.99	0.85 – 0.99		

Table 4: SNR measurements

	kV				
	80	**120**	**140**	**Student t-test**	**p-value**
Mean ± SD	0.09 ± 0.006	0.098 ± 0.002	0.1 ± 0.003	10.46	0.003
Min - Max	0.096 – 0.84	0.099 – 0.97	0.075 – 0.12		

3.1.Verification of electromechanical components

a) External lasers system

Since the gantry lasers were parallel and perpendicular to the scan plane. Wall lasers were orthogonal and parallel with the imaging plane and intersect with the center of the scan plane. The overhead laser was orthogonal to the imaging plane. The results showed that the accuracy of the three lasers was correct and comparable.

b) Couch and tabletop

The tabletop was orthogonal with the imaging plane, and level, couch, and tabletop motions were accurate. Also, the index and position under scanner control are accurate. The center holes located in the QA laser device were measured using the cursor tool option on the scanner as shown in figure 4. The location of the holes was less than 2 mm which was agreed upon. This agreement proves that the couch top axis of travel is perpendicular to the imaging plane. Figure 6 shows that the position under scanner control and indexing are accurate. Figure 6 shows that the tabletop does not contain any artifact-producing materials which can produce clinically significant image artifacts. All couch and tabletop tests were comparable and were in the accepted range.

c) CTDI measurements

The CTDI measurements are tabulated in table 7. The mean measured values of CTDI were 21.54, 29.31, 24.18, 21.98, and 26.03 at the center, 12, 3, 6, and 9 o'clock respectively. All CTDI values for the head phantom were within the tolerance limit for

the CT simulator compared with the formalisms in the AAPM Report 96 [18].

	10 % MTF			**50 % MTF**			**Student t-test**	**P-value**
	80 kV	**120 kV**	**140 kV**	**80 kV**	**120 kV**	**140 kV**		
Mean (lp/cm) ± SD	5.65 ± 0.13	5.7 ± 0.106	5.91 ± 0.077	3.22 ± 0.14	3.32 ± 0.085	3.4 ± 0.06	1.37	0.18
Min-Max	5.04 – 5.9	5.1 – 5.99	5.21 – 6.1	2.9 – 3.51	3.05 – 3.81	3.1 – 3.92		

Table 5: Performance of MTF derived from high contrast resolution module

Slice width reconstructed		**1.5 mm**		**5 mm**			**Student t-test**	**P-value**
	80 kV	**120 kV**	**140 kV**	**80 kV**	**120 kV**	**140 kV**		
Mean ± SD	1.56 ± 0.064	1.47 ± 0.075	1.41 ± 0.11	5.44 ± 0.023	5.409 ± 0.07	5.32± 0.09	0.657	0.014
Min-Max	1.33 – 1.78	1.38 – 1.69	1.42 – 1.61	5.1 – 6.08	5.07 – 6.02	5.12 – 5.91		

Table 6: The slice thickness measurements

Slice width reconstructed		**1.5 mm**		**5 mm**			**Student t-test**	**P-value**
	80 kV	**120 kV**	**140 kV**	**80 kV**	**120 kV**	**140 kV**		
Mean ± SD	1.56 ± 0.064	1.47 ± 0.075	1.41 ± 0.11	5.44 ± 0.023	5.409 ± 0.07	5.32± 0.09	0.657	0.014
Min-Max	1.33 – 1.78	1.38 – 1.69	1.42 – 1.61	5.1 – 6.08	5.07 – 6.02	5.12 – 5.91		

Table 7: $CTDI_{vol}$ measurements

Phantom	**Location**	**Mean$CTDI_{vol}$ (mGy) ± SD**	**Student t-test**	**P-value**
Head	Center12 o'clock 3 o'clock 6 o'clock 9 o'clock	21.54 ± 3.63 29.31± 1.56 24.18 ± 2.83 21.98 ± 3.17 26.03 ± 4.59	1.57	0.068

4- Conclusions

The image quality tests show comparable values with the AAPM acceptance testing protocol, where the CT, noise level, uniformity value, and SNRs were all within the accepted range. Also, the slice thickness accuracy and MTF tests show tolerable values. The external laser system tests show that the electromechanical laser components are accurate and work very well. The couch and tabletop positions were tested using the QA laser phantom, and all mechanical tests were accepted. In addition, the tabletop scanning at the zero position shows that the tabletop doesn't contain any artifact-producing materials. Moreover, the gantry index accuracy was tested using a ready-pack film irradiated twice with the same scan parameters, the lines from the two scans were superimposed which indicates that the gantry index is accurate. Finally, the CTDI measurements were tolerated and accepted according to the AAPM Report 96.

Therefore, the newly installed CT simulator

showed comparable performance and is validated for clinical use.

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