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Original Article

Commissioning a new CT simulator I: CT simulator hardware

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Abstract

This paper reports on the commissioning tests performed on a new GE Lightspeed RT wide-bore computed tomography (CT) scanner with GE Advantage Sim software. This paper focuses on the laser marking system, CT hardware and the interfaces between each component of the system, and generalises the findings to most CT simulation systems currently available. A discussion on the commissioning of the virtual simulator software will follow in a separate paper. Three phantoms were used (two constructed in-house) to assist with a range of tests covering aspects such as the laser patient marking system, CT hardware, and connections between the CT scanner, virtual simulator system and the treatment planning system (TPS) and VARiS. Tests performed showed the CT simulation system to be working within acceptable tolerances suggested in the literature, and baseline data have been obtained against which future comparisons of system performance have been made. Where no tolerances were available, we have suggested suitable values. While considering tolerances on Hounsfield number variation that may lead to a dose error in excess of 2%, we found that in the case of low-kV CT scanning the range of Hounsfield numbers for dense bone was outside the acceptable limits for potential dose errors and so users were advised not to perform radiotherapy planning CT scans with kV below 100 kV.

Keywords

Commissioning; CT simulation system; quality assurance

INTRODUCTION

Simulation continues to be an important part of the radiotherapy process for acquiring localisation data and treatment verification. Computed tomography (CT) simulation[1] is being increasingly implemented in this process to replace the simulation on a conventional simulator as it offers significant advantages:[2] (1) it offers the ability to acquire a complete volume data set; (2) it enables the generation of sophisticated digitally reconstructed radiographs (DRRs) for treatment portal verification; (3) having the data for the virtual patient for verification, it offers the possibility to miss out a patient visit for physical verification. The CT simulator consists of a diagnostic quality CT scanner with a flat patient couch, a computer-controlled moveable laser marking system and a virtual simulator (VS) workstation.

The acceptance testing and commissioning procedures carried out on a new CT simulator should evaluate each component of the system thoroughly in order to assess whether or not it meets with the specifications and acceptable tolerances, and to obtain baseline values against which future quality assurance (QA) of the systems can be measured. Currently, there is a dearth of information available on commissioning CT simulators;[3–6] therefore this report aims

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to set out the commissioning that was performed on the new CT simulation system (GE Lightspeed RT wide-bore CT scanner with GE Advantage Sim software v6) installed at the Northern Ireland Cancer Centre, and generalise that discussion to apply the guidelines applicable to most systems currently available. This paper concentrates on the laser marking system, CT hardware and the interface between each component of the virtual simulation system. A discussion on the virtual simulation software, including DRR generation and multimodality image registration, will follow in a separate paper.

METHODS

Commissioning tests can be sub-divided along functional lines for the system. The CT simulator involves an integration of several systems and so it is crucial that not only the individual systems themselves are tested but also the transfer of data between them (particularly coordinates) is tested for accuracy and robustness.

Phantoms

The tests a user performs will depend not only on the equipment specification but also on the available QA tools and phantoms. Commissioning and routine QA of a CT simulator consists of a significant range of tests, and most probably more than one phantom will be required to perform the all tests. When broken down into groups of similar tests, a few fairly simple phantoms are all that will be required and these could be constructed easily by an in-house mechanical workshop. A range of commercial phantoms are also available.[7,8] A commercial phantom, in particular, may be preferred for the assessment of Hounsfield number (HN) and electron density accuracy of the CT simulator, for example, the QUASAR phantom (SeeDOS Ltd.) and the CIRS phantom (Imaging Equipment Ltd./Southern Scientific). We have built a range of phantoms in-house for commissioning and routine QA. Figure 1 shows the laser check phantom, loosely based on a phantom available from Nuclear Associates. The phantom consists of a flat base-plate with a central 1-mm diameter ball-bearing. Twin pairs of crossed wires are positioned 10 cm each side of the centre, along the same axis. Marks are etched on the sides of the phantom, enabling it to be positioned in alignment with lateral lasers, and a spirit level on top enables the phantom to be levelled. This is useful as the flat-top couch insert may be removed, for example, to perform

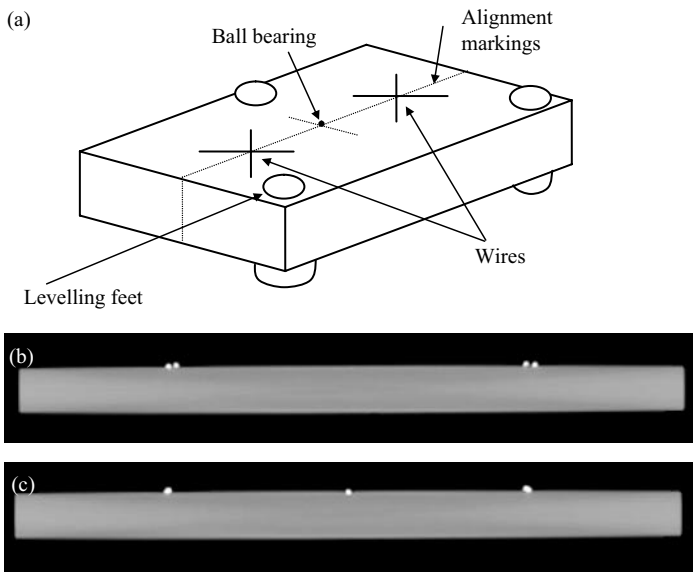

Figure 1. Laser check phantom and acquired 1.25 mm slice thickness CT images. (a) shows a schematic diagram of the phantom; (b) shows the central image when the phantom is aligned with lateral lasers offset in the Sup−Inf direction. When the phantom is aligned with lasers that have been correctly positioned, the three markers line up on the central slice, (c).

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a test on CT number uniformity with the CT manufacturer's QA phantom; and, in this case, although there are fixation screws at the end to lock it in position when it is replaced, there can still be a slight movement in the couch when it is 'locked'. Daily checks by radiographers on the unit can be done quickly and easily with a cube phantom (which assumes the couch to be level). This is a hollow plastic cube, typically 15 cm along its sides, with etched marks to align the phantom with the sagittal and lateral lasers, and 1-mm ball-bearings positioned centrally on lateral and anterior faces. We also have a simple Perspex and wire cube phantom to test the CT Sim and treatment planning process (Figure 2). This solid cube phantom (15 cm along each side) has a set of embedded wires that reproducibly define a PTV of known size and volume. Two ball-bearings positioned on the lateral faces and a centre line etched on the anterior face assist with alignment with the lasers.

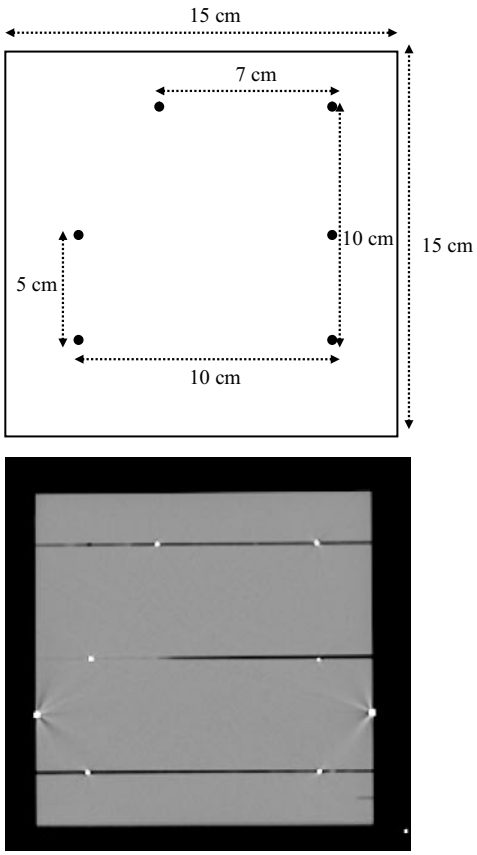

Figure 2. Schematic and central CT image of the Perspex and wire cube phantom showing the six wire markers and the two ball-bearings on either side of the phantom.

Laser marking system

In terms of the order of performing tests, it is useful firstly to ensure the laser marking system is correct and use this as a tool to check the CT couch geometry and movement. The laser system in situ may vary depending on the needs of a particular department, but, in general, available systems mainly vary in terms of the degree of motion of the lasers. Irrespective of the particular system installed, the same general set of tests is applicable for commissioning the laser marking system. In our department, a Dorado-3 system (L.A.P. lasers, Germany) was installed, consisting of two wall-mounted lateral lasers (with fixed vertical and moveable horizontal laser components) and a ceiling mounted tracking sagittal laser. A summary of the tests carried out on the laser marking system described in detail below can be found in Table 1.

The laser orientations in the horizontal and vertical must be tested to ensure they are true. For the vertical, this can be easily performed using a conventional plumb-line at commissioning and checked during routine QA by standing a long precision level vertically and ensuring the laser follows the edge of the level. A self-levelling laser-projection level (e.g. Fisco multi-point self-levelling 5-point laser, Fisco Tools Ltd, Essex, U.K.) is very useful in setting up the horizontal lateral lasers truly level. It can also be twisted out of plane of the lateral lasers to allow the horizontal lasers to be checked for trueness 'along the couch'. The lateral lasers must be coincident with each other in the vertical and horizontal orientations. This is easily checked using a small piece of film. Coincidence is especially important within a maximum patient volume positioned on the couch (within approximately 50 cm of isocentre in all three orthogonal directions). In the case of our Dorado-3 system, the overhead unit also projects a fixed lateral beam, which is coincident with the vertical beams from the lateral laser pair. This is somewhat surplus to the requirement, and may be turned off/blocked as it adds a further laser to be routinely checked

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Table 1. Summary of tests carried out on the laser marking system

System	Function	Test	Suggested tolerance	Results
Laser marking system	Reference mark marking	Laser setup accuracy	All laser positions accurate to within 1.0 mm[3] Angular divergence $<1^{\circ}$ over 100 cm[3]	Moveable laser positioning accurate to <0.5 mm over a range ± 50 cm from isocentre Laser offset from gantry accurate to 1.0 mm
		Co-ordinate transfer from virtual simulator	Error ≤ 1.0 mm at maximum positions[3]	Deviation <1.0 mm from planned position in all axes

and adjusted without adding any real value to the system setup. The sagittal laser should be coincident with the centre of the X-ray beam and, in turn, the patient couch should track the sagittal laser. Unlike a linac, where a base-frame system is used to ensure the patient couch and gantry are accurately perpendicular to each other, this design tends not to be the case for CT systems, even those for exclusive radiotherapy use. At commissioning, therefore, it is important to ensure that the couch is centred to the X-ray fan beam, and motion is found to be perpendicular to the X-ray beam. An X-ray opaque marker may be placed on the patient couch to mark the position of the sagittal laser. The marker should be ≤ 1 mm diameter to ensure the lasers meet a tolerance for accuracy of ± 1 mm. When imaged, any offset of the laser from X-ray isocentre (the centre of an image) can easily be obtained from the co-ordinates of the marker, either read directly from the CT image or after the images have been transferred to the VS and corrected. The marker can be moved down the patient couch, and a series of CT topograms quickly confirm the tracking of the couch with the laser.

The moveable lasers should display linearity of movement. This can be easily verified with a metre rule on the patient couch or using a metal tape measure placed and secured vertically for the lateral lasers. The installed LAP lasers performed with <0.5 mm deviations over a measured range of ± 50 cm from isocentre.

The lateral lasers will generally be installed at a known distance from the front of the gantry (typically 500 mm), allowing the final laser position to be fine-adjusted by the user. This provides ease of patient access for tattooing the laser marks.

First, the absolute offset should be checked. A phantom or opaque marker can be aligned with the lateral lasers, moved 500 mm into the gantry, and imaged to confirm (this assumes the calibration of couch longitudinal movement to have been checked previously). This avoids errors where the lateral lasers may be coincident, but angled to point towards or away from the gantry (in/out of axial plane). Second, two markers may be placed on the patient couch at a large distance on either side of the sagittal laser, in line with the lateral lasers, and set the marker position as the isocentre slice position (most scanners allow any z-position to be set as 'zero' or centre of the scan volume). With the acquisition of a set of thin (ideally 1-mm thickness or less) axial slices, the position of the markers will verify the offset of the lasers to gantry centre. In addition, if both lasers are at the same offset distance, both markers should appear with equal distinctness in each axial image. If this is not the case and one is out of alignment with the other along the z-direction, this indicates that the lasers are at an angle to the CT gantry. By placing another marker in line with the other two markers, but at the X-ray beam centre, an image showing equal distinctness for all three markers will ensure that the lateral lasers are truly running parallel to the X-ray fan beam and not orientated in or out of the plane of the image (i.e. verification that the lasers are truly parallel to the X-ray fan beam and that the offset is accurate to within ± 1 mm).

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The horizontal plane of the lateral lasers should coincide with the isocentre of the X-ray beam. This may be checked most easily using the two markers on the patient couch described earlier. Position the patient couch such that the markers are aligned with the lateral lasers. On an acquired image, their horizontal coordinate should be the same (this may be verified from the pixel coordinates or by overlaying a grid on the image). If this is not so, although the lasers may be coincident, they may be directed at an angle clockwise or counter-clockwise to true horizontal or the patient couch may not be flat. This can most easily be investigated and corrected using a laser projecting level.

It is possible on some systems to transfer the coordinates of the isocentre (or other reference point) from the VS to the laser system, which will cause the lasers to move to be aligned with this point. The function will be mentioned explicitly later.

CT hardware

A summary of CT hardware commissioning tests can be found in Table 2.

The commissioning of the CT scanner in terms of image quality, dosimetry and radiation protection generally falls within the remit of a Radiation Protection Advisor (RPA), and so is beyond the scope of this report. Details on this part of commissioning may be found on the IMPACT website: www.impactscan.org and in the IPEM Report 91.[9]

The CT couch should perform in the same manner as a treatment couch, in terms of accuracy and precision of movement and deflection (sag). At commissioning, the couch movement (loaded with weights simulating a typical adult patient) should be checked in the horizontal and vertical directions. In particular, it is important to be aware of the differences in couch design. The linear accelerator treatment couch design (often a so-called scissors type) and CT patient couch may differ, with some manufacturers (as in our case with a GE Lightspeed RT scanner) using a cantilever design for CT couch. This may result in differences in performance. Our checks on couch vertical motion were performed by attaching a marker to the couch and assessing the change in height indicated by the marker against the digital display over its full range of travel. The vertical accuracy and precision was found to be better than ±0.5 mm for vertical travel. Our GE Lightspeed RT CT couch with the cantilever design also means that any vertical movement will also include a horizontal movement. The system is engineered such that, with the gantry lasers on, the couch attempts to automatically correct any horizontal movement during vertical motion, to ensure the couch keeps to the same horizontal landmark during vertical motion. We found horizontal deviation during vertical movement to be $\leq$0.5 mm (gantry lasers on). In the horizontal

Table 2. *Summary of CT hardware tests*

System	Function	Test	Suggested tolerance	Results
CT scanner	Image acquisition	Dosimetry	±20% of manufacturer specifications[4]	
		Image quality	Consistent with manufacturer specifications and commissioning results[4]	
		HN accuracy and the effect of reconstruction kernels	Water: baseline ±5 HU[4]	Water: 4.3 ± 6.0 HU
		Accuracy and precision of couch motion under load	±1.0 mm over typical scan range[4] Table sag should be comparable to a medical linear accelerator[4]	<1.0 mm for typical patient scan <4.0 mm over full extension

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direction, a tape measure was attached to the couch and movement against digital display was assessed against a stationary marker. Again, horizontal deviation was better than ±0.5 mm. If the couch is not perfectly level in the superior–inferior direction, it is possible that as the couch extends there will be a difference in height between the superior and inferior ends. Setting up a projection laser level on a platform, such that it projects along the surface of the couch, checks how level the couch is, and extending the couch enables measurement of the deviation of the couch surface from the laser at the extremes of couch travel. We found the deviation from true horizontal to be less than 0.5 mm over the full range of horizontal couch travel.

At commissioning, it is important to verify that, in terms of sag under load, the CT patient couch will be performing in a similar way to the treatment couch. Further, it is important that there is minimal sag as the couch moves 500 mm from alignment with the external lasers, into the centre of the gantry. Most manufacturers have a specific procedure to measure couch sag, which will depend on the couch model (often involving the setup of a simple dial gauge under the superior couch end at maximum extension) and this should be followed and the results compared to data from sag of the treatment couch.

We loaded the couch with an evenly distributed 80-kg total load to model a typical patient. A marker was placed on the couch top and the couch height adjusted to align the marker and lateral horizontal laser. The couch was moved 500 mm into the gantry and the offset from the marker recorded: this was found to be <1 mm. Similarly, over full extension, sag was found to be <4 mm.

For radical treatments, image data from the CT are often used for dose calculation in the treatment planning system (TPS). The TPS will take the HNs and convert them to electron densities for dose calculation, and so it is important to measure the HNs and confirm the correct calibration of the scanner. The HNs will depend mainly on X-ray tube kV, mA and image reconstruction kernel. Several phantoms are commercially available, containing a number of inserts that mimic the HNs of the most common tissue types. The scanner will generally be calibrated with reference to air and water, so these represent a minimum for acquired data, although data for a bone insert are also valuable. A series of scans using typical clinical parameters should be acquired to measure the HNs. The scan data should be transferred to the TPS and the corresponding electron densities measured. In order to obtain baseline values for CT numbers and determine tolerances, a CT phantom (CIRS Model 062 Electron Density Phantom) containing 17 different tissue equivalent inserts was scanned a number of times using the acquisition protocols as listed in Table 3. The protocols covered a range of available values for mA, kV and reconstruction kernels. Acquisition protocols 6 and 7 are considered to be the clinical standard or default protocol in our department; therefore, the CT numbers obtained using these protocols are considered the baseline for comparisons.

Table 3. Acquisition protocols

Scan	Scan mode	kV	mA	Kernel	Slice thickness
1	Axial	120	80	Std	5 mm (1 image per rotation, 4 × 1.25 mm detectors)
2	Axial	120	200	Std	5 mm
3	Axial	120	400	Std	5 mm
4	Axial	80	100	Std	5 mm
5	Axial	140	100	Std	5 mm
a				Lung	
b				Bone	
c				Detail	
d				Edge	
e				Soft	
6	Helical	120	100	Std	5 mm (pitch 0.75:1)
7	Helical	120	100	Std	5 mm (pitch 1.5:1)

An important consideration is the tolerance on HN/electron density variation, which may lead to a dose error in excess of 2%. Using a methodology described in Kilby et al.,[10] for a 6 MV linac photon beam irradiating a depth of 20 cm of water, 10 cm of lung or 7 cm of bone, a 2% error in dose is produced with a change of electron density of ±0.03 for water, ±0.05 for lung

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and ±0.08 for bone (Table 4). Advantage Sim does not give the user electron density information, so data were transferred to our TPS. The TPS uses the relations detailed in Knoos et al.[11] to determine electron densities based on HNs, and this formalism was used to generate electron densities and help define tolerances. Our results (see Table 5) showed that the range of HNs for dense bone was out of the acceptable limits for potential dose errors. HN variation is generally greatest for bone, and for low-kV CT scanning. Our low-kV scan produced an unacceptably high HN for bone, and so we advised the users not to perform radiotherapy planning CT scans with kV below 100.

If post-processing filters are used, which affect the HNs (on Siemens CT scanners, for example), these should be included.

Table 4. *Hounsfield numbers and electron densities for water, lung and dense bone*

	HN	Electron density ($\times 10^{23}$ electrons/cm^3)	Tolerance (±)
Water	4.3	3.31	0.03
Lung (inhale)	−820	0.55	0.05
Dense bone	960	4.82	0.08

Table 5. *Hounsfield numbers and electron densities with varying kV for dense bone*

Scan	kV	mA	HN	Electron density
1	80	100	1320	5.26
2	120	100	960	4.82
3	140	100	895	4.74

For the GE Lightspeed CT scanner, the scan field of view (SFOV) is 50 cm and corresponds to a maximum display field of view (DFOV). Using the 'WideView' option allows the CT image to be reconstructed with a DFOV of 65 cm. In order to obtain a qualitative assessment of the efficacy of this algorithm, our Perspex and wire phantom was scanned at the edges of the SFOV and the 'WideView' option used to reconstruct images with a DFOV of 65 cm. These images were assessed as being geometrically correct.

Data transfer

CT simulation is only one step in the larger treatment process. Data will be flowing through the CT simulator, and therefore the speed and robustness of data transfer must be assessed. Archiving is the simplest data transfer protocol, but arguably one of the most important. On most VS systems, archiving can be done both locally onto recordable media (CD-R, DVD, MOD and exabyte tape). It is a simple matter to send some studies to and back from archive, and check for data integrity via standard checksum methods. Speed of transfer can be assessed qualitatively in this situation.

Interface between the CT scanner and the VS

Once the patient CT data have been acquired, the data are transferred to the VS. This link must be tested to ensure the integrity of the data transfer (Table 6). A test phantom (geometric or anatomical) should be scanned in all clinical patient orientations and the images transferred

Table 6. *Summary of tests on the CT scanner-virtual simulator interface*

System	Function	Test	Suggested tolerance	Results
CT scanner-virtual simulator interface	Image and co-ordinate transfer	Transfer accuracy	Successful transfer of all CT data[3]	Successful transfer of all CT data Correct transfer of patient orientation
		Transfer speed and robustness	Speeds within tolerances set at commissioning for all times of day[3]	Data transfer speeds satisfactory

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Table 7. Summary of tests carried out on the virtual simulator—database interface

System	Function	Test	Suggested tolerance	Results
Virtual simulator—database interface	Transfer of images, structures and plans to the radiotherapy database (e.g. VARiS)	Accuracy of data transfer Speed of data transfer	Accurate transfer of all data Speeds within tolerances set at commissioning for all times of day[1]	Successful transfer of all images, structures and plans to VARiS

to the VS to ensure the transferred images are displayed with the correct orientation. A qualitative assessment of transfer may also be made to ensure the network is performing as expected. To test the CT-VS interface, our Perspex and wire phantom containing a number of wire markers that could be used for the purposes of reproducible contouring (see Figure 2) was scanned in four different patient orientations (head-first, supine; feet-first, supine; head first, prone; and feet-first, prone) and the images transferred to the VS. The images were checked for correct orientation. The system was found to be robust.

Interface between the VS and the laser marking system

During the planning process on the Advantage Sim VS, a 'marking' file is created and can be exported and retrieved by a compliant laser marking system, which then moves the lasers to the specified coordinates ready for patient setup checks. The origin of the coordinate system used by Advantage Sim is defined as the point of intersection of the CT gantry axis and the scanning plane when the table is in the zero offset position. All co-ordinates used and displayed by Advantage Sim are defined relative to this point. The co-ordinate system is referenced to the centres of the voxels. A scan of the Perspex and wire phantom was acquired and transferred to the VS. An off-centre isocentre was defined at a known geometric position, and the coordinates of the reference laser positions were exported to the LAP laser system. The couch was moved to the landmarked zero position, and the lasers were then automatically driven to the newly defined isocentre position. Deviation from planned isocentre was <1 mm in all axes.

Interface between the VS and the TPS/PACS/record and verify systems

Once structures/plans/DRRs have been generated using virtual simulation, the data will generally be sent to a TPS (for dose calculation), or directly to the department record and verify system (such as VARiS) for conventional verification or treatment, via a network. As above, transfer tests should be done on the data to ensure accuracy and robustness of transfer (Table 7). Figure 3a and b shows examples of CT scans transferred from VS to TPS, where the CT orientation was misinterpreted resulting in its display as differing to the overlaying structure contour. Figure 3c shows an example where two different test contours were drawn manually. When transferred from the VS to the TPS all contours imported onto 1 CT slice. Depending on workflow, some departments may additionally return the plan data to the VS system for verification and generation of geometric setup shifts and DRRs of higher quality than their TPS. In this situation, the robustness of data transfer is important in terms not only of bit-wise integrity of the data but also of accuracy of parameters and coordinates. Specifically, when data are moving between systems, it is important that the geometry and scales (i.e. IEC/non-IEC scales for machine movement, patient orientations, MLC leaf labelling and so on) are not confused at any point. It is useful to acquire a set of phantom scans in the four typical patient orientations, generate a plan on these data sets and transfer them through the anticipated work-flow for the departmental treatment. A set of standard plans can be generated and used for routine QA in a similar fashion. The process described in the previous section for checking transfer of orientation was further extended to include

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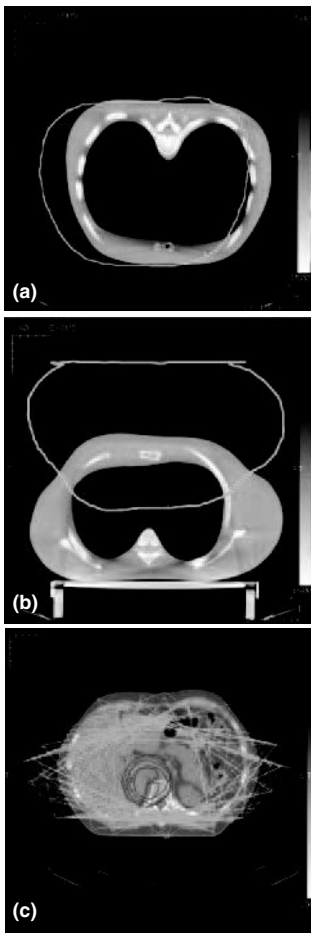

Figure 3. Examples of inaccurate data transfer between the virtual simulator and the treatment planning system. (a) CT patient orientation is reversed (a) head-first to feet-first, (b) supine to prone, and (c) all structure contours are drawn on the central CT slice only.

geometric coordinates. The CT scans were sent to the VS and contoured using the wire marker pattern in the phantom, and a standard two-field plan applied with known isocentre coordinates, field setup shifts and DRRs. These structures and plans were then exported to the TPS and VARiS. The integrity of coordinates, structures and plan parameters were checked and found to be correct.

SUMMARY

We have presented a detailed report on the commissioning tests performed on the mechanical components of a new CT simulator (GE Lightspeed RT wide-bore CT scanner with GE Advantage Sim software) installed at the Northern Ireland Cancer Centre. We have attempted to generalise the discussions to be applicable to the performance on most CT simulation systems currently available.

Phantoms required for initial commissioning and subsequent quality control tests, both available commercially and constructed in-house, have been described.

Tests carried out on the laser marking system, the CT scanner hardware and the interfaces between the CT scanner and the VS and between the VS and the laser marking system/TPS/PACS/Record and Verify systems have been described. The system was generally found to be working within suggested tolerances obtained from literature currently available, and where there are no tolerances available, we have suggested suitable values. However, while determining tolerances for HNs, by considering the variation that may lead to a dose error in excess of 2%, it was found that in the case of low-kV CT scanning, the range of HNs was outside the acceptable limits for potential dose errors.

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