Canadian Association of Provincial Cancer Agencies

Standards for Quality Control at Canadian Radiation Treatment Centres

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CT-Simulators

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Developed, revised and submitted for approval by THE CANADIAN ORGANIZATION OF MEDICAL PHYSICISTS and THE CANADIAN COLLEGE OF PHYSICISTS IN MEDICINE

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Document development and review process: The quality control documents in this series originated from one of two sources. Some of the source documents were commissioned by CAPCA specifically for the purpose of developing national standards. Others had been previously developed for provincial use by the Physics Professional Affairs Committee of Cancer Care Ontario (formerly the Ontario Cancer Treatment and Research Foundation). The source documents were developed over an extended period of time from 1989 onwards. Each source document was reviewed by one or more independent Canadian medical physicists and the reviews accepted by the task group as they became available. The primary and secondary task group reviewers then examined the source document, the external review(s) and any appropriate published literature to propose quality control standards, objectives and criteria to the full task group. The full task group met electronically and, by a consensus approach, approved the present document. The task group gratefully acknowledges the effort contributed by the author(s) of the source document and the reviewer(s) whose work forms the basis of this document. Extensive review, updating and reformatting have been performed and, for any errors or omissions introduced in this process, the task group takes full responsibility.

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Acronyms, Synonyms and Definitions

AAPM	American Association of Physicists in Medicine
ADCL	Accredited Dosimetry Calibration Laboratory
Al	Aluminum
ANSI	American National Standards Institute
BSF	Back-scatter factor
CAPCA	Canadian Association of Provincial Cancer Agencies
CCO	CancerCare Ontario
CCPM	Canadian College of Physicists in Medicine
CNSC	Canadian Nuclear Safety Commission (Successor to the Atomic Energy Control Board - AECB)
COMP	Canadian Organization of Medical Physics
CSA	Canadian Standards Association
CT	Computed Tomography
CTV	Clinical target volume
Cu	Copper
EPI(D)	Electronic portal imaging (device)
FWHM	Full width at half maximum
Gleason score	A numerical system based on major and minor histological patterns
Gy	Gray, unit of absorbed dose (1J/kg)
HVL	Half-value layer
IAEA	International Atomic Energy Agency
ICRU	International Commission on Radiation Units and Measurements
IEC	International Electrotechnical Commission (Geneva, Switzerland)
IMRT	Intensity modulated radiation therapy
INMS-NRCC	Institute for National Measurement Standards of the National Research Council of Canada
IPEM	Institution of Physics and Engineering in Medicine
IPSM	Institute of Physical Sciences in Medicine
ISO	International Organization for Standardization

Isocentre	The intersection of the axes of collimator and gantry rotation
Linac	Electron linear accelerator
MLC	Multileaf collimator
mMLC	mini- or micro-Multileaf Collimator
MPPAC	Medical Physics Professional Advisory Committee
MRI	Magnetic Resonance Imaging
MU	Monitor unit
NCRP	National Council on Radiation Protection and Measurements
NIST	National Institute of Standards and Technology
NRCC	National Research Council of Canada
NTD	Normal treatment distance
ODI	Optical distance indicator
PMMA	Polymethyl methacrylate
PDD	Percentage depth dose
PSA	Prostate specific antigen
PTV	Planning target volume
QA	Quality assurance (the program)
QC	Quality control (specific tasks)
SSD	Source-to-surface distance
SRS	Stereotactic radiosurgery
SRT	Stereotactic radiotherapy
STP	Standard temperature and pressure
TBI	Total body irradiation
TG-	Publications of various AAPM Quality Assurance Task Groups
TLD	Thermoluminescent dosimeter
U	air-kerma strength (μGy m^2/h)
WHO	World Health Organization
σ	Standard deviation
ε_T	Timer/monitor end error

Frequencies:

Daily:	Once during every treatment day and separated by at least 12 hours.
Weekly:	On average once every 7 days and at intervals of between 5 and 9 days
Monthly:	On average once every four weeks and at intervals of between 3 and 5 weeks
Annually	On average once every 12 months and at intervals of between 10 and 14 months.

Output:

Output constancy check: a daily instrument reading (corrected for temperature and pressure) taken under reproducible geometrical conditions designed to check that the radiation output (e.g. cGy/MU) values in clinical use are not grossly in error.

Output Measurement: a determination of the absorbed dose to water (cGy) at a reference point in the photon beam for a chosen field size and beam quality.

Introduction

Patients receiving treatment in a Canadian cancer centre have a reasonable expectation that the quality of their treatment is independent of their geographic location or the centre they are attending. Insofar as medical physicists contribute to treatment quality, this expectation will be more closely met through the harmonisation of quality control standards across the country. The Canadian Association of Provincial Cancer Agencies (CAPCA) has initiated the process of standardisation of treatment quality in Canada through its draft document "Standards for Quality Assurance at Canadian Radiation Treatment Centres". This present document is an appendix to the CAPCA document and is concerned with quality control standards for use with CT simulators. The source document upon which this standard is based was commissioned specifically for this purpose.

A quality control program on equipment used for radiation therapy in a Canadian cancer centre must be carried out by, or under the direct supervision of, a qualified medical physicist. Here, a qualified medical physicist is a physicist who is certified in Radiation Oncology Physics by the Canadian College of Physicists in Medicine or who holds equivalent certification. This individual, known as the supervising physicist, is responsible for ensuring compliance with the local quality control protocol, maintaining appropriate documentation, taking appropriate remedial actions and communicating with other members of the radiation therapy team concerning the operational state of the equipment. Depending on local circumstances and organisational structure, one physicist may supervise quality control on all equipment or the responsibilities may be dispersed. However, the supervising physicist for a particular piece of equipment must have a direct line of communication to the Quality Assurance Committee for the Radiation Treatment Program.

This document contains specific performance objectives and criteria that the equipment should meet in order to assure an acceptable level of treatment quality. In a departure from previous formats, this document contains two Appendices which provide more technical details on the equipment and recommended tests. It is the responsibility of the supervising physicist to ensure that the locally available test equipment and procedures are sufficiently sensitive to establish compliance or otherwise with the objectives and criteria specified here. There are many other publications dealing with the performance, specifications and quality control of CT-simulators (please see the References and Bibliography at the end of this document). Most of these publications have extensive reference lists. Some have detailed descriptions indicating how to conduct the various quality control tests.

Radiation safety activities are beyond the scope of this report. However, such activities may be integrated into routine quality control programs of equipment.

A successful quality assurance program is critically dependent upon adequately trained staff and a culture of continuous quality improvement. Educational opportunities to be offered to quality control staff must include new staff orientation, in-house continuous

education, conference participation and manufacturer's courses as appropriate. All such educational activities must be documented as part of the quality assurance program. Continuous quality improvement embodies the concepts of documentation, monitoring, review and feedback.

The standards promoted in this document are based on the experience of the authors and reviewers and are broadly consistent with recommendations from other jurisdictions (AAPM, 1993; IPEM, 1999; Sixel, 2001; Mutic, 2003). Although this document has undergone extensive review it is possible that errors and inaccuracies remain. It is hoped that the users of these standards will contribute to their further development through the identification of shortcomings and advances in knowledge that could be incorporated in future versions.

Performance Objectives and Criteria

Objectives and criteria for the evaluation of the performance of radiotherapy equipment fall into several categories.

1. Functionality. Systems for which the criterion of performance is "Functional" are either working correctly or not. Such systems are commonly associated with the safety features of the equipment or installation. Operating a facility which has failed a test of functionality has the potential to expose patients and staff to hazardous conditions.

2. Reproducibility. The results of routine quality control tests, for which reproducibility is the criterion, are assessed against the results obtained at installation from the accepted unit. Tolerances and action levels may be set for parameters that can be quantified. An example is field flatness. For characteristics that are not readily amenable to quantification on a routine basis, such as image quality, criteria have to be developed locally to reflect the test equipment available and inter or intra-observer variability as appropriate.

3. Accuracy. Accuracy is the deviation of the measured value of a parameter from its expected or defined value. Examples are isocentre diameter and reference dosimetry (cGy/MU).

4. Characterisation and documentation. In some cases it is necessary to make measurements to characterise the performance of a piece of equipment before it can be used clinically. An example is the measurement of the ion collection efficiency.

5. Completeness. The use of this term is restricted to the periodic review of quality control procedures, analysis and documentation.

For quantities that can be measured, tolerance and action levels may be defined.

i. Tolerance Level. For a performance parameter that can be measured, a tolerance level is defined. If the difference between the measured value and its expected or defined value is at or below the stated tolerance level then no further action is required as regards that performance parameter.

ii Action Level. If the difference between the measured value and its expected or defined value exceeds the action level then a response is required immediately. The ideal response is to bring the system back to a state of functioning which meets all tolerance levels. If this is not immediately possible, then the use of the equipment must be restricted to clinical situations in which the identified inadequate performance is of no or acceptable and understood clinical significance. The decision on the most appropriate response is made by the supervising physicist in conjunction with the users of the

equipment and others as appropriate. If the difference between the measured value and its expected or defined value lies between the tolerance and action levels, several courses of action are open. For a problem that is easily and quickly rectifiable, remedial action should be taken at once. An alternative course of action is to delay remedial intervention until the next scheduled maintenance period. Finally, the decision may be made to monitor the performance of the parameter in question over a period of time and to postpone a decision until the behaviour of the parameter is confirmed. Once again, this will be a decision made by the supervising physicist in consultation with the users of the equipment and others as appropriate.

Documentation of equipment performance is essential and is discussed later. However, at the conclusion of a series of quality control tests it is essential to inform the users of the equipment of its status. If performance is within tolerance verbal communication with the users is sufficient. If one or more parameters fails to meet Action Level criteria, and immediate remedial action is not possible, then the users of the equipment must be informed in writing of the conditions under which the equipment may be used. Compliance with Action Levels but failure to meet Tolerance Levels for one or more parameters may be communicated verbally or in writing depending on the parameters and personnel involved. The judgement of those involved will be required to make this decision.

System Description

The purpose of radiation planning simulation is to 'simulate' as accurately as possible the patient's position, shape, and anatomy relative to the radiation therapy machine and isocentre (Coia, 1995; Gerber, 1999; Purdy. 2001). Modern treatment machines are able to achieve mechanical accuracies in the range of ± 1 mm and ± 1^{o} and so too, must the 'simulators' used to plan these radiation treatments. The process of radiation therapy planning frequently involves (1) the acquisition of a volumetric CT dataset, (2) the transfer of the CT dataset to a radiation therapy planning workstation, (3) the marking of patient-based reference points before or after virtual beam planning, (4) localization of targets and critical structures, (5) virtual beam planning, and (6) dose calculations. For the purpose of this document, steps 1, 2, and 3 define the process of CT-simulation. Steps 1, 2, 3, and sometimes 4, occur with the patient present in the CT scanner room.

CT simulators consist of a state-of the-art spiral (or helical) CT scanner (Brink, 1995; Fishman, 1995), the associated acquisition/processing computer system, a patient laser marking system, and radiation therapy accessories. CT images provide the anatomical, geometrical, and relative electron density information necessary for the precision radiation planning. The CT computer is networked to a 3-D virtual simulation workstation or full radiation therapy planning (RTP) system. These workstations provide software tools for the localization of the targets, co-registration of the CT images with other imaging modalities, the graphical planning of the radiation beams, and the production of digitally-reconstructed radiographs (DRRs) in a beam's eye view (BEV). The difference between 3D virtual simulation workstations and full RTP systems is the dose calculation and dose evaluation capabilities that are integral with the latter. The process of CT simulation has been described in detail by various authors (please see References and Bibliography).

A more detailed description of CT simulators and accessories may be found in Appendix A.

Acceptance Testing and Commissioning

CT-simulators that are newly acquired or substantially upgraded require acceptance testing before being put into clinical service. Acceptance tests have three purposes:

- to ensure that the unit meets stated specifications,
- to establish baseline parameters for the future quality control program,
- to familiarize the customer with operation of the unit.

In addition acceptance testing of the equipment and facility will include establishing compliance with applicable radiation safety codes. These are included in federal and/or provincial regulations and it is the supervising physicist or designate's responsibility to be familiar with these requirements and to demonstrate compliance. Decommissioning of radiotherapy equipment and facilities may also be regulated by provincial and/or federal authorities.

The vendor in general does not provide acceptance tests for CT scanners although specifications are available. Therefore, the purchaser must plan and execute all tests required for acceptance (Kalender, 1991; Loo, 1994). The purchaser should complete all tests to their satisfaction, before which formal purchase of the unit should not be completed.

The standards for CT-simulator acceptance testing should be consistent with routine quality control objectives and criteria. In particular, there is no reason why a new or upgraded CT-simulator, and its associated safety systems, should not meet the Tolerance Levels detailed later in this document (Table 1). Optical, mechanical, radiographic and safety tests must be included. Several of these tests are based on an existing HARP (Healing Arts Radiation Protection) document, the X-ray Safety Code, Reg. 543 (Healing Arts Radiation protection Act, Ontario, 1990). The tests should be performed by, or under the supervision of, a qualified medical physicist.

Adherence to these standards (Table 1) must be demonstrated and documented, in or outside of the vendor's acceptance testing protocol, before a new simulator or major upgrade is accepted, and put into clinical service. Also, an appropriate subset of acceptance tests must be performed after any repair or preventive maintenance interventions on the simulator. The extent of testing required must be judged by a qualified medical physicist.

Commissioning generally refers to the acquisition of additional measured data from a unit after most acceptance testing is completed, with two purposes:

- for subsequent calculations, for example, involving radiation dose,
- to establish baseline parameters for the future quality control program.

For CT-simulators, the latter purpose dominates commissioning and in fact, is similar to acceptance. For CT-simulators, the former purpose deals mostly with the measurement of CT numbers under various scan techniques, to generate the CT number to relative electron density curve required for dose calculations. Clearly all the tests listed in Table 1 must be performed at this time with the intended local test equipment and protocols if meaningful baselines are to be established.

More details on these topics may be found in Appendix B.

Quality Control of Equipment

The purpose of a quality control program is to assure that operational standards for a unit that were considered acceptable at time of purchase continue to be maintained, as closely as possible, over the life of the unit. Thus, quality control tests typically are periodic repetitions, partial or full, of acceptance and commissioning tests. For simulators, tests are required for optical, mechanical, radiographic and safety systems.

The standards for CT simulator quality control are listed in Table 1. These minimum standards consist of tests to be performed, along with their minimum frequency. The tests are derived from the published literature and, in particular, the standards laid out in the AAPM document, TG-40, (AAPM, 1994) and the IPEM document, Report 81 (IPEM, 1999). The Tolerance Level is typically set at 50-75% of the Action Level.

The tests should be performed by a qualified medical physicist, or a suitably trained individual working under the supervision of a qualified medical physicist. Independent verification of the results of quality control tests is an essential component of any quality control program. To ensure redundancy and adequate monitoring, a second qualified medical physicist must independently verify the implementation, analysis and interpretation of the quality control tests at least annually. This independent check must be documented.

Daily tests must be scheduled at the beginning of each working day. For other tests, testing at less than the minimum frequency is permissible only if experience has established that the parameters of interest are highly stable. Documentary evidence supporting this decision is essential. It is unlikely that a frequency of less than half that specified here could be justified.

In the event that the equipment does not meet the stated performance objectives and criteria, an adjustment or repair should be effected. If it is not immediately possible to restore the equipment to full performance, then the use of the equipment must be restricted to clinical situations in which the identified inadequate performance is of no or acceptable and understood clinical significance. The decision on the most appropriate response is made by the supervising physicist in conjunction with the users of the equipment and others as appropriate

Preventive maintenance schedules and interventions are recommended by the manufacturer of the equipment and should be adhered to diligently. Following preventive maintenance or repair, the appropriate quality control tests selected from those listed in Table 1 must be performed before the unit is returned to clinical service. The extent of testing required must be judged by a qualified medical physicist. Frequently, machine repairs and quality control testing are performed by different persons. In such cases, good communication and reporting between the various staff involved are essential.

As pointed out previously, radiation safety activities are beyond the scope of this report. However, such activities may be integrated into routine quality control programs of equipment.

Documentation

Appropriate documentation is an essential component of a quality assurance program. All documents associated with the program should contain, as a minimum, the following information:

1. the name of the institution
2. the name of the originating department
3. the name of the developer of the document
4. the name of the individual or group who approved the document for clinical use
5. the date of first issue
6. the number and date of the current revision

Further guidelines on the design of appropriate documentation may be found elsewhere (ISO 1994, Quality 2000)

Documents for use in a quality control program may be conveniently separated into two major categories: protocols and records. The protocols must be included in the Policy and Procedure Manual of the Radiation Treatment Quality Assurance Committee.

The quality control protocol contains the standards, or performance objectives and criteria, to be applied to the piece of equipment. Such standards are based on documents such as this. In addition to the specification of standards, the protocol should provide sufficient detail on the test equipment and procedures to be followed that there can be no residual ambiguity in the interpretation of the test results.

The quality control record contains the results of the tests, the date(s) on which they were performed and the signatures and qualifications of the tester and the supervising physicist. When the number of tests to be performed on a particular occasion is limited and the test procedure is simple it may be advantageous to combine the protocol and record into a single document.

In addition to the protocol and record, it is essential to have a means of documenting any corrective action that takes place together with any subsequent tests. Deviations from the locally approved protocol, such as those resulting from clinical pressure to access the equipment, must, of course, also be documented.

Finally, all documentation related to the quality control program must be retained for at least ten years.

Table 1: Quality Control Tests for CT-Simulators

Designator	Test	Performance	
		Tolerance	Action
Daily			
DS1	Door interlock	Functional	
DS2	Beam status indicators	Functional	
DS3	Emergency off buttons (Alternate daily)	Functional	
DS4	Lasers: parallel to scan plane	1°	2°
DS5	Lasers: orthogonality	1°	2°
DS6	Lasers: position from scan plane	1	2
DS7	Couch Level: lateral & longitudinal	0.5°	1°
DS8	Couch motions: vertical & longitudinal	1	2
DS9	CT number accuracy of water - mean	0 ± 3 HU	0±5 HU
DS10	Image noise	5 HU	10 HU
DS11	Field uniformity of water	5 HU	10 HU
DS12	Simulated planning	1	2
Monthly			
MS1	Lasers: parallel to scan plane	1	2
MS2	Lasers: orthogonality	1°	2°
MS3	Lasers: position from scan plane	1	2
MS4	Lasers: linearity of translatable lasers	1	2
MS5	Couch Level: lateral & longitudinal	0.5°	1°
MS6	Couch motions: vertical & longitudinal	1	2
MS7	Gantry tilt	1°	2°
MS8	Records	Complete	
Semi-annually			
SS1	Slice localization from pilot	0.5	1
SS2	CT number accuracy of water - mean	0 ± 3 HU	0±5 HU
SS3	CT number accuracy of other material - mean	*	
SS4	Field uniformity of water – std deviation	5 HU	10 HU
SS5	Low contrast resolution	10 @ 0.3%	#
SS6	High contrast resolution (5% MTF)	5 lp/cm	**
SS7	Slice thickness (sensitivity profile)	0.5	1
SS8	X-ray Generation : kV and HVL	2 kV	5 kV
SS9	X-ray Generation: mAs linearity	5%	10%
Annually			
AS1	Radiation Dose (CTDI)	5%	10%
AS2	Independent quality control review	Complete	

Tolerance and Action Levels are specified in millimetres unless otherwise stated
* CT number accuracy of other materials will depend on the material and its uniformity. Set tolerance at the time of acceptance.

** High contrast resolution tolerance and action level will depend on the scan technique used. Set tolerance at the time of acceptance.
# Low contrast resolution will depend on the scan technique. Vendors quote 3-5mm at this contrast level but this is seldom achieved with large FOV simulation protocols.

Notes

Daily Tests

DS1,2,3	The configuration of these tests will depend on the design of the facility and equipment. Safety is the concern and tests should be designed accordingly. As a minimum, manufacturer's recommendations and applicable regulations must be followed.
DS4,5,6	Alignment of lasers should match minimally the tolerance set for those in the treatment delivery rooms. Laser lines should also be parallel to three principal axes of the images.
DS7,8	Couch level should be checked daily as the RT table top is an add on device. For daily checks, these tests are performed with no load. The motions should be in directions parallel to the principal axes of the images. Most new couches will be better than 0.5 mm.
DS9	CT number of water should be checked using a typical CT-simulation protocol and a cylindrical water phantom.
DS10	Standard deviation of water in ROI at image centre using a typical CT-simulation protocol and a cylindrical water phantom.
DS11	Maximum deviation of the mean CT# in any ROI from the mean CT# in an ROI at the centre of a cylindrical water phantom.
DS12	To verify the complete CT-simulation process, it is recommended that a simulated planning test be part of a quality assurance program. A phantom with various markers can be scanned with a CT-simulation protocol, the images transferred and virtually simulated, and marked with the lasers according to the laser/couch output data.

Monthly Tests

MS1-6	As per daily but over total range of motions.
MS7	Digital gantry angle readouts must be verified using a spirit level for gantry 0^{o}.
MS8	Documentation relating to the daily quality control checks, preventive maintenance, service calls and subsequent checks must be complete, legible and the operator identified.

Semi-annual Tests

SS1 Slice localization from pilot should be checked over the total scannable length of the couch with a typical load.

SS2-9 CT image performance is highly dependent on the scan technique used. For QA purposes, a standard QA protocol should be established and used for all image performance checks. Tolerances should be established at acceptance testing. Vendors provide automated calibration or QA software tools. These tools provide tolerances and action levels for each specified acquisition technique for both image and x-ray performance parameters.

Annual Tests

AS1 CTDI should be measured annually or when there is a change in the tube model that may affect x-ray output. CTDI is measured in units of dose and the tolerance and action levels refer to deviations from the manufacturer's specification.

AS2 To ensure redundancy and adequate monitoring, a second qualified medical physicist must independently verify the implementation, analysis and interpretation of the quality control tests at least annually.

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Appendix A: System Design

This appendix deals with the basic features of CT-simulators. Enhanced options such as ultra-fast CT, multi-slice CT, quantitative CT, 4DCT, and CT virtual endoscopy are beyond the scope of this document.

A.1 CT Scanner and Computer Console

The major components of a CT scanner can be divided into four major systems: the mechanical system, the imaging system for data acquisition, the data processing system, and the system control including storage and connectivity functions. Basic CT design varies little across manufacturers with 3rd and 4th generation scanners being the most common. With the advent of slip ring technology (i.e., conduction of electricity through the contact of a stationary brush with a moving metal ring), continuous rotation is possible allowing CT scanners to perform spiral scanning. Spiral CT scanning involves continuous data acquisition throughout the volume of interest by simultaneously moving the patient through the gantry while the x-ray source rotates. It is the acquisition method used predominately for CT-simulation. For a detailed description of spiral technology, the reader is referred to the literature [Brink, 1995; Fishman, 1995]. Vendors offer scanners with single or multiple slice capabilities per revolution. The major benefits of multiple slice capabilities over single slice are (1) faster acquisition times such as those required in dynamic studies such as 4DCT, (2) near isotropic voxels, and (3) patient throughput. Faster acquisition times, decreased tube loading of multi-slice scanners (which will allow longer volumes to be scanned in a single acquisition), and near isotropic voxel dimensions can potentially provide an advantage over single-slice systems for CT-simulation purposes. For planning, patient throughput is a minor factor, as the majority of time in the scanner room is spent on patient positioning, manufacturing of immobilization devices, and patient marking.

Basic design and capabilities of modern CT scanners are listed in Table A.1. This table is not intended to be comprehensive, but rather provide information of typical ranges.

Table A.1 Basic Design of CT Scanners

System	Component	Capabilities (Some results are technique dependent)
Mechanical	Aperture Size Gantry Couch Couch Level	Diameter 70 cm to 85 cm Tilt range ± 30^o (not compatible with RTP systems) Accuracy better than 0.5 mm with maximum load Motion range: Vertical 35 to 70 cm Vertical within bore 10 to 15 cm Scannable longitudinal 100 to 180 cm Maximum load: 135 to 215 kg Deviation < 0.5^o, in all positions and with load
Operating Modes	Projection scans Axial scans Spiral scan	AP, Lateral views Manual or programmed multi-series Pitch factor range: 0.5 to 2 Single run beam on time minimum 60 sec Multiple programmable spiral acquisitions
Imaging System	Anode heat storage Anode cooling rate Power generator kVp mA Detectors Slice collimation	Range 3.5 to 8.0 MHU Minimally 550 KHU/minute Typically 30 kW or greater Range 80 to 140 kVp Range 50 to 400 mA Range 1000 to 4800 with detection efficiency of greater than 85% : solid state or gas ionization Single slice to 64 slice arrays Range 0.25 to 10 mm 'thickness' per image
Image Performance	Noise Uniformity of water MTF Low contrast resolution	0.3% to 0.5% mean: 0 ± 2 with SD<8 Range 3 to 20 lp/cm depending on scan technique Range 0.2 to 0.6%
Storage	On-line Archival	Minimally 2GB for image storage 8mm data tape, optical disk or CD-rom writer

The requirements for CT simulation differ significantly from those of conventional diagnostic imaging and hence, so too the desired capabilities of the CT scanner. The special requirements for CT-simulation and the rationale are listed in Table A.2. The major requirements in scanning for CT simulation are (1) excellent low contrast resolution for target localization, (2) high spatial resolution in the cranial-caudal direction through the use of thin slices to improve resolution on digitally-reconstructed radiographs (DRRs), (3) accurate geometries and CT numbers for dose calculation purposes, and (4) accurate geometric simulation of patient position and shape relative to a treatment machine. .

Optimal low contrast resolution is critical for target localization and delineating tumour boundaries. Tumours are often surrounded by soft tissues of similar densities that make delineation of the tumour difficult. Improvements in low contrast resolution can be achieved using high mAs per image and appropriate filters. In 3-D radiation planning, a

large patient volume must be imaged using thin slices (typically 2 to 5 mm) in spiral mode in as short as time possible. Large volume scanning will facilitate multiple and/or non-coplanar beam planning as well as provide DRRs with adequate perspective for comparison with verification images. The resolution in this direction must be sufficient to allow physicians to identify anatomic landmarks such as inter-vertebral spaces and the carina. To mimic the treatment geometry, all CT data should be acquired under normal respiration in as short as time as possible (typically less than 2 minutes) to reduce the risk of gross patient motions which can introduce anatomic misalignments and inaccuracies into 3D reconstructions, multi-planar reconstructions (MPR), and DRRs. Figure 1 is an example of the type of geometric error that can occur in a MPR with gross patient motion during the scan acquisition. To this end, a compromise must be made between maximum mAs per image and scan length since tube cooling periods during the scan acquisition period should be avoided. Therefore, the CT scanner X-ray tube must have large heat anode loading and heat dissipation capabilities to withstand the very high heat loads associated with the high demand spiral techniques that are typical of CT-simulation.

Finally, since the volumetric data are used for beam planning and dose calculations, the data must be accurate in terms of geometry, patient position and shape, and CT numbers. Since the CT simulation images must duplicate the patient position on the treatment unit, a large CT bore opening and flat table top are requirements to enable scanning with the patient in radiation therapy position with all ancillary devices in place. For accurate CT numbers, the image reconstruction FOV must be sufficiently large as to encompass all of the patient and ancillary devices. Material and any part of the patient intercepting the x-ray beam beyond the FOV will lead to errors in reconstructed CT numbers and geometry data for dose calculations. Unfortunately, large FOV will also result in a reduction of spatial resolution in the transaxial plane.

Thus priorities of a CT scanner for CT simulation include high anode heating, large power generator, extended spiral capabilities, spatial integrity, large FOV, and a bore diameter and couch that will accommodate all treatment positions without compromise. These and other considerations for CT-simulation have been discussed in the literature [Coia, 1995; van Dyk, 1999; van Dyk, 2000].

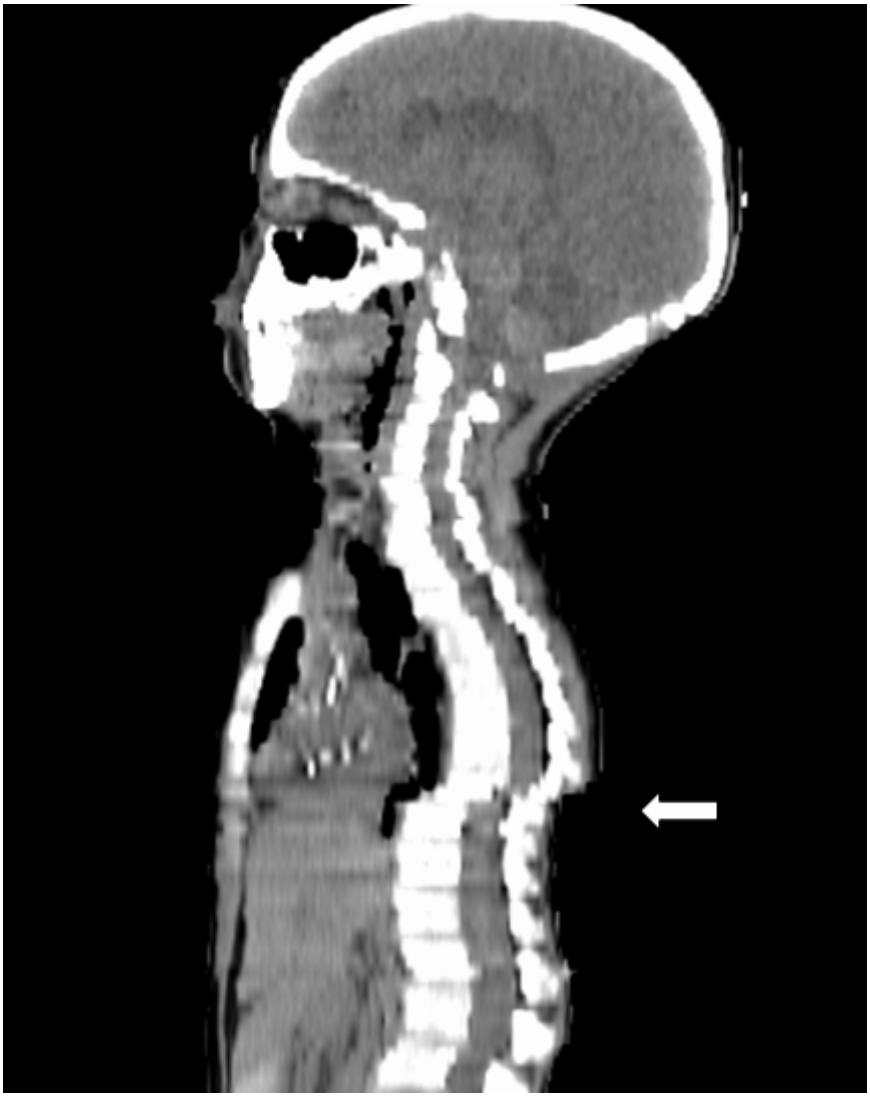

Figure 1 - A sagittal MPR illustrating the geometric Distortion (arrow) that can occur with gross patient motion during volumetric scanning.

Table A.2 Scanning Requirements for CT-Simulation

SCANNING FOR CT SIMULATION	RATIONALE
Mechanical System:	
1. Large diameter bore	• Accommodate treatment position and all accessories
2. Radiolucent, flat table top	• Replicate treatment position
3. Accurate table motions & indices	• Localization and field placement accuracy
4. Couch level & parallel to axis of rotation	• Accurate simulation of treatment position & beams
Imaging System: Data Acquisition	
1. Large volume acquisition; extended spiral capabilities	• Accommodate non-coplanar, large field, or multi-beam planning
2. Thin Slice (typically 1 to 5 mm)	• Improve cranial-caudal resolution for DRRs, MPRs, and 3D reconstructions
3. Fast total acquisition times	• Minimize gross motion artifacts for DRRs, MPRs, and 3D reconstructions
4. High mAs	• Improve low contrast resolution for soft tissue localization
5. High tube loading; fast anode cooling	• Facilitate scan techniques and minimize gross motion artefacts; efficient scanner utilization
6. Detectors with high x-ray geometric and detection efficiency	• For fast, high-quality image acquisition
Imaging System: Data Processing	
1. Large field of reconstruction (FOV)	• Impacts image quality and dose accuracy if patient anatomy is outside field
2. Accurate CT numbers	• Impacts dose calculations
3. Range of pitch	• Impacts cephala-caudal resolution for DRRs, MPRs, and 3D reconstructions
4. Spatial Integrity	• Accurate replication of treatment position
System Control, Storage and Connectivity:	
1. Ultra-fast CPU	• Fast reconstruction, display, etc.
2. Large image storage	• A volumetric study has 100s of images at about 0.5 MB each
3. DICOM transfer	• Require fast transfer of images in DICOM to other RT workstations for patient marking

A.2 CT console/computer system

For CT-simulation, the requirements for the CT computer system are similar to those for diagnostic purposes. In CT-simulation, a large volume of data is collected with images numbering between 80 and 300. With the large number of images and the possible need for patient laser marking with the patient still within the scanner room, an ultra-fast CPU for image reconstruction is required of the CT computer system. Typical processing time per axial image ranges from 2 second to sub-seconds in state-of-the-art

scanners. If patient laser marking of the actual treatment beams are to be performed, the CT computer system must be able to perform fast DICOM transfers to the virtual simulation or RTP workstation order to minimize the time that the patient must remain in treatment position. Automatic transfer of images as soon as they are reconstructed is a desirable feature for CT-simulation.

A.3 Laser Marking System

Although most commercial scanners are equipped with on-board lasers, these are seldom used in CT-simulation. The on-board lasers are often mounted on the rotating frame of the CT scanner and hence, are unstable and thus, can be inaccurate. For CT-simulation, an external laser marking system is installed at distances typically 50 cm away from the scan plan along the scan axis. This distance between the laser marking system and the CT gantry is required to allow radiation therapist access to the patient and space to re-position the patient if necessary. A laser marking system is required to transfer beam placement locations (e.g., isocentre) from the virtual simulation software to the skin of the patient lying on the CT couch or to establish reference skin marks for treatment set-up. For CT-simulation, the laser system is integrated with the coordinate space of the CT images. This establishes a patient-based coordinate system that can be used for daily treatment set-up. It also links a patient-based coordinate system to an image-based coordinate system.

There are two main configurations in laser marking systems. The simplest system consists of 3 lasers; 2 fixed lateral lasers defining fixed coronal and transverse planes, and one ceiling-mounted laser defining a sagittal plane that can be translated in the medio-lateral direction.This system can be used to generate a simple co-planar 3-point set-up where the 3 orthogonal laser planes intersect. The translatable laser is controlled by an analogue or digital device. In this type of system, the couch vertical and longitudinal travel capabilities are used to determine antero-posterior and cranial-caudal position in the patient, respectively, while the translatable laser is used to establish medio-lateral position. In the second system, the lateral coronal plane lasers can be translated as well (in the vertical direction) so couch vertical travel is not required. A separate computer is required to download coordinates, maintain calibration files, and control laser movements. Each translatable laser requires routine calibration. In all systems, tolerance in positional accuracy should be better than ± 1mm with lines parallel to true vertical and true horizontal and to the principal image planes.

A.4 Radiation Therapy Accessories

Since the purpose of CT-simulation is to simulate the patient on the radiation delivery unit, patient positioning and reproducibility are important during CT acquisitions and this is the key differentiator from diagnostic CTs. To create the identical positioning, radiation therapy accessories are required during the patient scanning. These accessories are dependent on the treatment technique to be used and generally include a flat table top and immobilization devices including arm poles, masks, angled boards, shells, moulds,

etc. At many centres, consideration should also be given to the mounting of a stereotactic frame onto the CT table top. Any accessory used for CT-simulation should not contain any metallic components, as these will cause significant beam hardening artifacts on the CT images.

The CT-simulation scanner table must have a radio-transparent flat top similar in dimensions to those on radiation treatment machines. The width of the table top should match that on the treatment units to ensure adequate support for arms and positioning of side-mounted devices such as arm poles. Additionally, it should accommodate commercially available registration devices. The registration device allows the patient immobilization device to be moved from the CT scanner to a treatment machine in a reproducible manner. In terms of level, motions, and load capacity, the table should have specifications similar to that for linear accelerator treatment tables.

Appendix B: Acceptance Testing and Quality Assurance

Acceptance testing and quality assurance programs for CT scanners for diagnostic purposes have been well established [AAPM, 1993; NCRP, 1988; McCullough, 1995; McCullough, 1980]. While CT scanners for radiation therapy require image quality comparable to those of diagnostic facilities, additional emphasis is placed on the geometric accuracy of the mechanical, optical, and imaging systems. Standards for acceptance and quality assurance of CT simulators, specifically, have only been developed recently. The most comprehensive document is that produced by AAPM task group 66 and is entitled "Quality assurance for CT simulators and the CT simulation process: Report of the AAPM Radiation Therapy Committee Task Group No. 66" [Mutic, 2003]. Other publications on the acceptance and quality assurance of CT-simulators have also been published [Gerber, 1999; Coia, 1995; van Dyk 1999; van Dyk 2000]. It is important to note that some test results are dependent on the CT model, the options installed, and the scanning technique. The tolerances set in Table 1 should be obtainable by most 3rd and 4th generation scanners.
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B.1 Radiation Safety: Radiation Survey and Interlocks

Radiation safety for staff, patients, and the public must be evaluated for all medical devices which emit ionizing radiation. Radiation levels measured about the vicinity of a CT scanner is predominately a result of scatter from the patient [AAPM 1988]. At the time of purchase, vendors may supply a radiation dose map similar to that shown in Figure 2, with site planning documents and this can be used as a guide. The survey should be conducted with scattering medium representative of a typical patient on the CT couch using a high acquisition technique. A large volume scatter ion chamber (typically greater than 300 cm^3) such as that pictured in Figure 3, connected to a digital electrometer is the standard instrument for area survey about a diagnostic x-ray unit. Air kerma rates measured at 1 m from the scanner range from 1 x 10^{-3} to 4 x 10^{-3} mGy/mA-min based on axial scanning [AAPM 1993]. Areas to be surveyed include the control room, the entrance to the scanner room, and all surrounding hallways and rooms including those on floors immediately above and below the CT suite. In conjunction with estimates of workload and oocupancy, the physicist must determine whether or not the measured levels comply with current regulatory limits. In Canada, the CT scanners are licensed by provincial agencies while the radiation protection limits are regulated by the Canadian Nuclear Safety Commision (CNSC).

The safe operation of a CT scanner also includes the evaluation of all emergency stops, interlocks and warning lights that must be tested routinely for proper operation. Some emergency stops are designed to arrest power to the CT gantry only while others will shut off power to both the gantry and CT computer. The installation of interlocks will vary with each CT scanner room. Minimally, there should be door interlocks preventing the x-ray beam from turning on in the event that the interlock is not engaged.

Ideally there should also be an interlock between the control room and the scanner room to minimize the risk of accidental staff exposure.

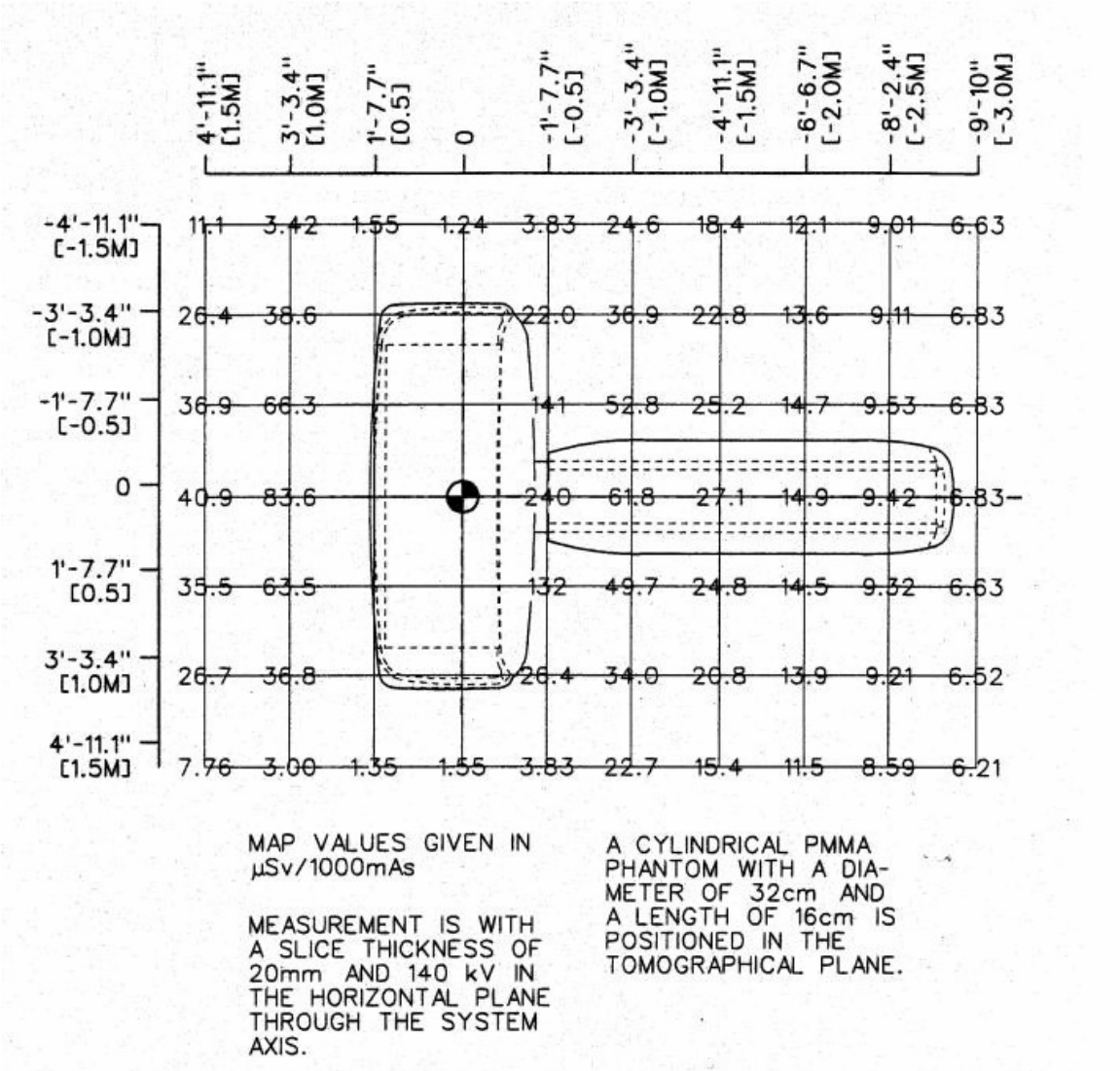


Figure 2 - Example of a radiation survey map about a CT scanner. These maps may be provided by the vendor to help guide the installation and survey.

Figure 3 - A large volume (300 cm^3) ion chamber used in radiation survey of diagnostic equipment.

B.2 CT Dosimetry

The radiation dose within the patient volume scanned during a CT scanning procedure depends primarily on the nominal slice thickness, the mAs, the kV, and compensation. Since much of the dose to any one slice is a result of scatter from adjacent slices, dose determination to any one point must account for scatter contribution from all contributing tomographic slices. The CT Dose Index (CTDI) [DHSS, 1984; Spokas, 1982] is the most common parameter defined to represent the integrated dose to one point in an axial scan and is defined as "the integral of dose profile along a line perpendicular to the tomographic plane divided by the product of the nominal tomographic section thickness and the number of tomograms produced in the single scan";

$$CTDI = \frac{1}{nT}\int_{-\infty}^{+\infty} D(z)dz \qquad (1)$$

where: z is the position along a line perpendicular to the tomographic plane, D(z) is dose at position z, T is the nominal tomographic section thickness, and n is number of tomograms produced in a single scan. The CTDI has been defined for axial scanning only. A spiral pitch of 1 would be expected to produce the same CTDI as for axial scanning with the same technique while increasing the spiral pitch beyond one would result in a lower CTDI for the same given collimation and technique. The relative dose decreases as the inverse of the pitch factor [McNitt-Gray, 1999].

Standard methods for measuring diagnostic x-ray exposures have been developed [AAPM, 1990; Loo, 1994]. The standard instrument for CTDI measurement is a 10 cm^3 pencil ion chamber [Suzuki, 1978]. These chambers are designed to integrate exposure over the length of the chamber, collecting the primary and scattered dose from a single axial scan. The reading is equivalent to the exposure at the center of a series of contiguous slices spanning the length of the chamber. Since in practice the CTDI chamber is 10 cm long, CTDI measurements should be made over the distance of 100 mm. This quantity is known as $CTDI_{100}$. Further details on CTDI and the calculation of CTDI from measured charge values are available in the published literature[DHSS, 1984; Spokas, 1982; Shope, 1981].

The CTDI dose phantoms (Figure 4) are circular cylinders with holes to extend the pencil ion chamber through the slice plane. The holes are positioned at the centre, at the 12 o'clock, 3 o'clock, 6 o'clock, and 9 o'clock positions. The head phantom measures approximately 16 cm in diameter while the body phantom measures 32 cm. Measurements near the centre of the body phantom are typically half of those at the surface.

Table B.1 shows examples doses from an axial scan using 130 kV, 250 mAs, and an 8 mm slice thickness. CTDI values will increase with increasing mA, kV, and time. For CT-simulators specifically, exposure is unlikely to be a major issue for patients being planned for radiation therapy. Nevertheless, CTDI values must be measured to ensure proper performance of the x-ray generating system.

Table B.1. Example CTDI dose in cGy from an axial scan using 130 kV, 250 mAs, and 8 mm slice thickness.

Position	Centre	12 o'clock	3 o'clock	6 o'clock	9 o'clock
Head Phantom Dose (cGy)	4.1	5.0	4.8	4.4	4.7
Body Phantom Dose (cGy)	1.2	3.0	3.0	2.6	2.9

Figure 4 - The CTDI Head and Body Phantoms and the 10 cm ion chamber

B.3 CT Image Performance

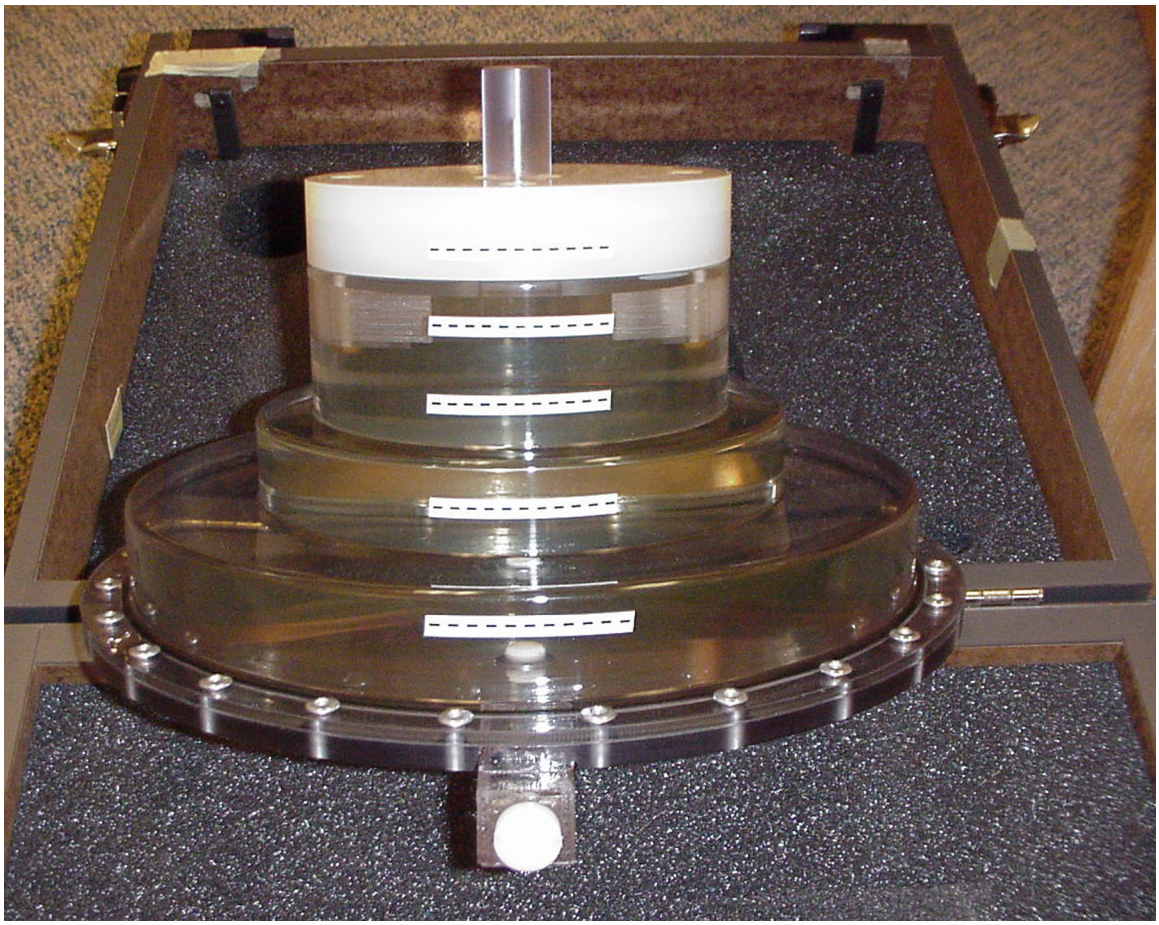
Acceptance testing procedures of image performance of CT scanners for diagnostic facilities have been well documented [AAPM, 1993; McCullough, 1995; McCullough, 1980; Loo, 1994; Kalender, 1981; Polacin, 1994; AAPM, 1977]. Standard CT image performance parameters that should be measured or characterized include noise, uniformity, low contrast resolution, high contrast resolution, slice width and sensitivity profiles, CT number accuracy, artefact evaluation and spatial integrity. AAPM TG-1 report 39 addresses CT image performance associated with axial-mode scanning only [AAPM, 1993]. Since spiral scanning is used almost exclusively in CT simulation, contrast and resolution along the z-axis (i.e., longitudinal axis) must also be evaluated. Kalender and Polacin have shown that most standard performance parameters of the transaxial images including spatial resolution, image uniformity, and contrast are not affected by spiral scanning at the same technique. The major effect of spiral scanning is on the slice sensitivity profile, a function of table feed per 360^{o} of scan rotation [Kalender, 1991]. If the spiral pitch, defined as the table increment per gantry rotation divided by the collimation, is too large or the spiral interpolator poor, broad sensitivity profiles result with a corresponding loss of z-axis resolution. This in turn affects the partial volume averaging and the accuracy of MPRs and DRRs.

Purchasers should be aware that vendor specifications are typically for their highest diagnostic techniques which are typically for small FOV, high mAs, thick slice, and ultra-high resolution filters. CT-simulation is seldom performed with these types of techniques. Therapy physicists need to focus on those scanning techniques, which are commonly used for therapy simulation. Simulation protocols have high mAs, but are always thin slice with large FOV, which consequently restricts users to medium resolution, smooth filters. To ensure accurate dose calculations by Radiation Treatment Planning Systems, it is important that the patient and associated immobilization devices reside within the requested reconstruction FOV. Therefore, FOV is seldom much less than 30 cm in diameter for CT-simulation with a corresponding reduction in image resolution. For an image size of 512 x 512 voxels, a FOV of 30 cm limits voxel resolution to 0.58 mm while a typical pelvis protocol FOV of 48 cm would be limited to 0.94 mm. To ensure CT number accuracy near the edge of the reconstruction FOV, the scan FOV should be at least as large as the reconstruction FOV. Note that some current CT scanners offer an “extended reconstruction FOV” which is larger than the scan FOV.

The parameters that require testing are briefly summarized in Table B.2. Performance tolerances will depend on the specific scanner, manufacturer's specifications, and scan parameters used. Table B.2 provides performance tolerances for a typical acquisition protocol for radiation planning. For field service use as well as quality assurance, almost all models of modern CT scanners are equipped with automated performance testing and evaluation software as well as automated calibration software. At the time of scanner acceptance, physicists should verify that these software tools are functional and give results that can be independently verified. Once validated, the use of these automated performance software tools can be used for trouble-shooting as well as bi-annual quality assurance.

Image performance can be measured using a variety of vendor-supplied or commercially-available phantoms. Vendors will generally provide a performance phantom similar in design to that recommended by AAPM Report #1 and an example is shown in Figure 5 [AAPM, 1977]. The performance phantom recommended by AAPM report #1 was designed for evaluation of axial scanning. One common, commercially-available phantom for CT performance and QA is the CATPHAN by the Phantom Laboratory (Salem, NY) is shown in Figure 6. The mention of this commercially-available phantom in this document does not necessarily constitute endorsement of their use.

For commissioning of a CT scanner before clinical use, the conversion of CT numbers to relative electron densities must be determined using materials of known densities and different scan techniques. An example of a commercially-available phantom containing inserts of various known densities is shown in Figure 7. By scanning such a phantom under all the acquisition protocols to be used therapy planning, a mean curve of CT number to relative electron densities can be generated such as that shown in Figure 8. This curve is unique for each scanner and required for use by the RTP systems.



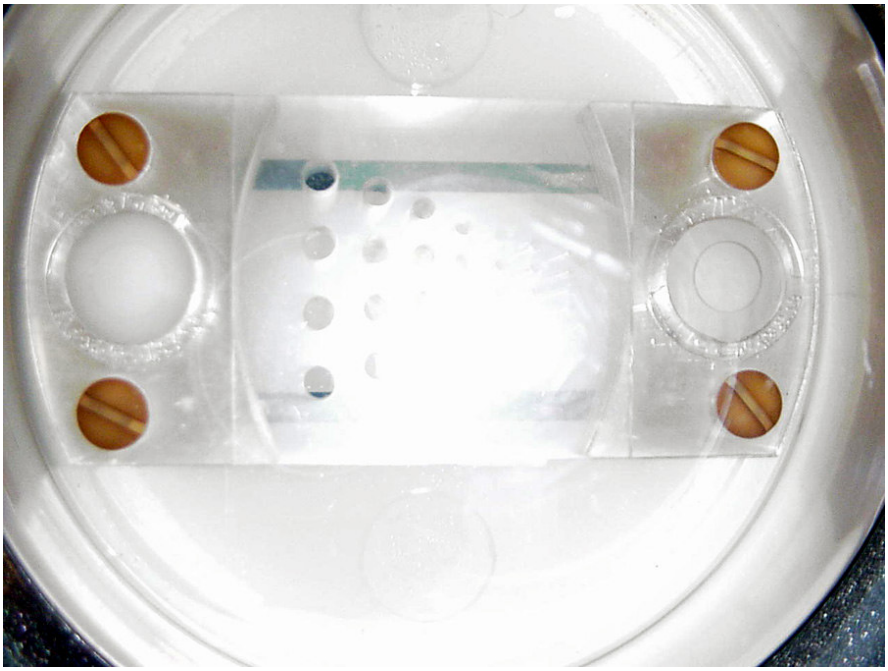


Figure 5 - AAPM-based CT Performance Phantom

Figure 6 - Commercially-available CT performance phantom.

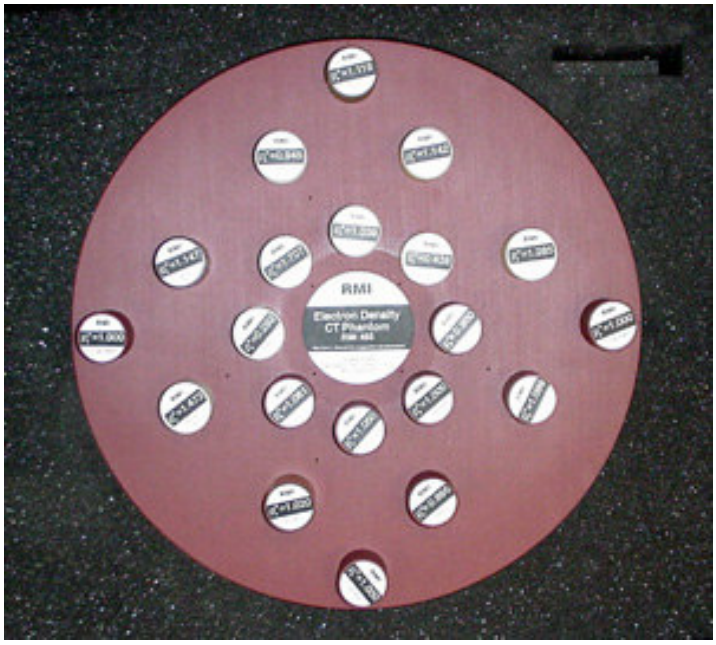


Figure 7 - Example of a phantom containing inserts of various densities. This type of phantom can be used in the determination of a CT number to relative electron density curve for an RTP system.

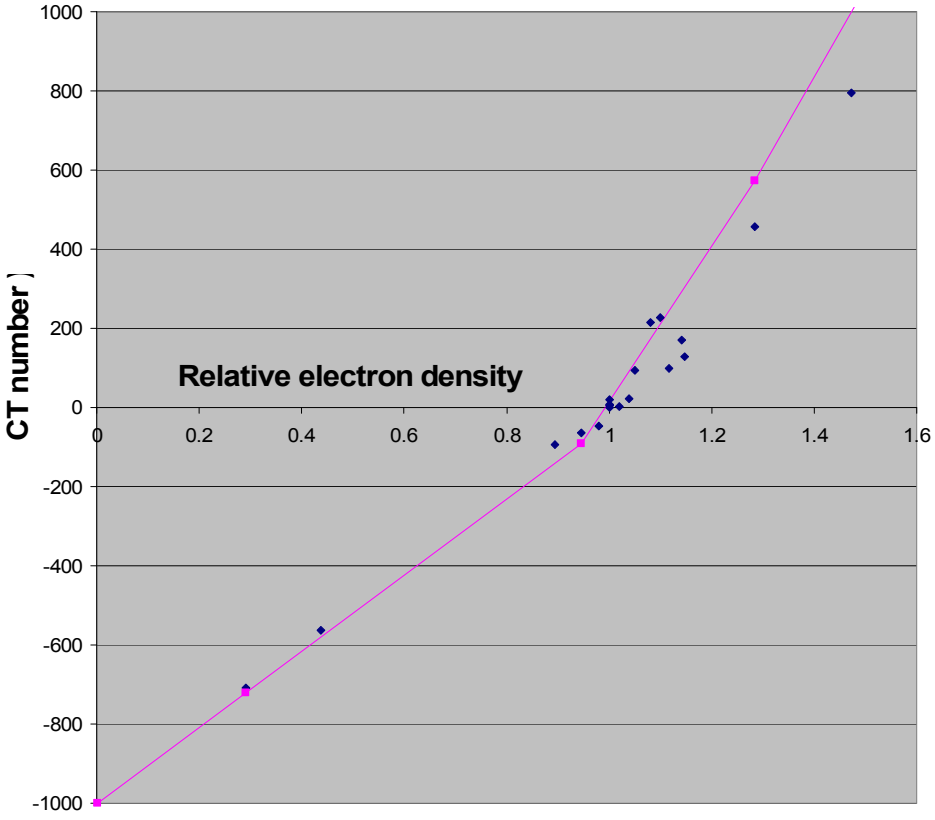


Figure 8 - Example of a CT number to relative electron density curve for a CT scanner.

Table B.2 Performance Testing for a CT-Simulator

System	Test Parameters	Tolerance
Mechanical	**Couch (with & without load)**	
	Alignment with rotational axis	Parallel
	Couch with image plane	Orthogonal
	RT couch insert	Level ≤ 0.5°
	Couch : level with vertical motion	Level ≤ 0.5°
	Level with longitudinal motion	Level ≤ 0.5°
	Couch: longitudinal motion with readout	0.5 mm
	Vertical motion with readout	0.5 mm
	Loaded couch: increment check	0.5 mm/ 1°
	Gantry tilt	1°
Image Quality/Tube Performance	Slice localization from pilot image	0.5 mm
	X-ray Generation:	
	kVp	*± 2 kV
	HVL	*
	mAs linearity	*± 5%
	Collimation:	
	Slice thickness (sensitivity profile)	* ± 0.5 mm of nominal
	Image Quality:	
	Spatial accuracy	± 1 pixel
	CT number accuracy – water	0 ± 3 HU
	- other materials	± 10 HU
	Uniformity – water	σ < 5.0 HU
	Low contrast	* 0.25 to 0.55%
	MTF (modulation transfer function)	* 5% at 6 lp/cm
Radiation and Safety	Emergency stops	functional
	Dose (depends on technique)	≤ 5 cGy

* typical values only. True tolerance depends on scanner model, scan parameters and set-up

B.4 Mechanical Accuracy and Stability

In addition to these standard tests of CT image performance, greater emphasis must be placed on testing parameters associated with couch mechanics, spatial integrity,

and CT number accuracy. For CT-simulation, the accuracy of the volumetric dataset used for localization and beam planning depends on the integrity of the couch indexing and its relationship to the imaging and laser marking systems.

To mimic radiation treatment, the patient support assembly including the flat table top must have specifications similar or better to those on the treatment units. First, the level of the couch top in both lateral and longitudinal (i.e., parallel to scanner axis) must be measured with and without full load. Tolerance should be better than $0^{o} \pm 0.5^{o}$. Measurements should be taken throughout the range of scannable motion. Secondly, the couch longitudinal motion should be parallel to the scanner axis (i.e., z-axis of the images) and its motion linear to better than ± 0.5 mm with full load. Similarly, the couch vertical motion should be orthogonal (i.e., follow y-axis of images) to the scanner axis and its motion linear to better than ± 0.5 mm with full load. Finally, once the mechanical movements are verified with the digital read-outs, the slice localization from pilot or scout images should be tested. Again tolerance should be better than ± 0.5 mm.

B.5 Laser Marking System

For a three-point system, tests should be performed to assess orthogonality of the lasers, its distance from the scan plane along the scan axis, and the linearity of any moving laser. At the reference position, the ceiling and lateral lasers should coincide with the principal axes of the image, x and y, respectively. Tolerances should be comparable to those set for lasers within a radiation treatment unit. The accuracy of reference point or isocentre marking by the lasers should be tested in conjunction with the virtual simulation software on a daily basis.