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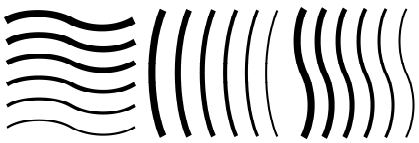
Quality Assurance for Tomotherapy Systems

NEDERLANDSE COMMISSIE VOOR STRALINGSDOSIMETRIE

Report 27 of the Netherlands Commission on Radiation Dosimetry
March 2017



Netherlands Commission on Radiation Dosimetry
Subcommittee Tomotherapy QA
March 2017

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Quality Assurance for Tomotherapy Systems

NEDERLANDSE COMMISSIE VOOR STRALINGSDOSIMETRIE

Report 27 of the Netherlands Commission on Radiation Dosimetry

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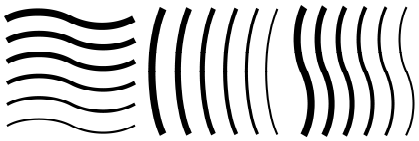

Netherlands Commission on Radiation Dosimetry

Subcommittee Tomotherapy QA

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Preface

The Nederlandse Commissie voor Stralingsdosimetrie (NCS, Netherlands Commission on Radiation Dosimetry, http://www.radiationdosimetry.org) was officially established on 3 September 1982 with the aim of promoting the appropriate use of dosimetry of ionising radiation both for scientific research and practical applications. The NCS is chaired by a board of scientists, installed upon the nomination of the supporting societies, including the Nederlandse Vereniging voor Radiotherapie en Oncologie (Netherlands Society for Radiotherapy and Oncology), the Nederlandse Vereniging voor Nucleaire Geneeskunde (Dutch Society of Nuclear Medicine), the Nederlandse Vereniging voor Klinische Fysica (Dutch Society for Medical Physics), the Nederlandse Vereniging voor Radiobiologie (Netherlands Radiobiological Society), the Nederlandse Vereniging voor Stralingshygiëne (Netherlands Society for Radiological Protection), the Nederlandse Vereniging voor Medische Beeldvorming en Radiotherapie (Dutch Society for Medical Imaging and Radiotherapy), the Nederlandse Vereniging van Klinisch Fysisch Medewerkers (Dutch Society for Medical Physics Engineers), the Nederlandse Vereniging voor Radiologie (Radiological Society of the Netherlands) and the Belgische Vereniging voor Ziekenhuisfysici/Société Belge des Physiciens des Hôpitaux (Belgian Hospital Physicists Association). To pursue its aims, the NCS accomplishes the following tasks: participation in dosimetry standardisation and promotion of dosimetry intercomparisons, drafting of dosimetry protocols, collection and evaluation of physical data related to dosimetry. Furthermore, the commission shall maintain or establish links with national and international organisations concerned with ionising radiation and promulgate information on new developments in the field of radiation dosimetry.

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Summary

This NCS report on ‘QA for Tomotherapy Systems’ is written by medical physicists from Belgium, France, Germany and the Netherlands, all experienced users of the Tomotherapy systems. Note the use of the multiform of the word ‘system’: Tomotherapy is an integrated system with sub systems for dose calculation, image acquisition, dose delivery, adaptive radiotherapy, quality assurance and transfer of the patient beam prescription (sinogram) to another Tomotherapy machine. After the publication of the AAPM report ‘QA for Helical Tomotherapy: report of the AAPM Task Group 148’ in 2010, various (sub)systems have been updated and improved, warranting an update of this code of practice. This subcommittee started its work in September 2009.

Major progress has been made on automated and integrated Quality Assurance, taking advantage of arrays of detectors (third party vendors), using the build-in MVCT exit detector for QA and by the introduction of the TQA application which integrates acquisition and analysis of QA data. The introduction of the non-rotating target made beam energy more stable. The dose control system (*DCS*) made output more stable. Both developments had its impact on the QA program.

Another field of progress concerns protocols for small field reference dosimetry, specific for machines unable to set-up a conventional reference field, like Tomotherapy. The dosimetry protocol described in this report is mainly based on the report of the IAEA/AAPM working group on a new formalism for reference dosimetry of small and non-standard fields.

Dose Planning has evolved also, resulting in VoLO: a Tomotherapy specific implementation of the Collapsed Cone Superposition algorithm implemented on a Graphical Processor Unit hardware platform. This report contains a chapter on dose planning with a detailed description of these developments, its history and present-day recommended QA. Furthermore, QA of the MVCT imaging beam, the patient set up correction tools and the applications for sinogram transfer and adaptive procedures are described.

The basis of this code of practice is the Tomotherapy system as it was established in 2015. Developments which were in progress while finishing this report, like dose planning by a third party vendor, advanced tools and workflow for adaptive radiotherapy, the use of the exit detector for in vivo dosimetry and a build in kV imaging system. These are left to a future report.

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Glossary of concepts, accessories and system components

Helical Tomotherapy	Radiotherapy unit dedicated to IMRT, using a linac that produces a fan shaped beam that rotates continuously around the patient while the couch transfers the patient through the field. A binary MLC is used to shape the beam segments and intensity is modulated by allowing individual leaf open times per projection.
Projection	A projection is one of the 51 equally spaced arc segments per rotation. In a projection the binary MLC is programmed to open one or more leaves a fraction of the time needed to travel a projection.
MLC	The binary Multi Leaf Collimator (MLC) is used to shape the beam segments. The MLC consists of 64 pneumatic (air driven, motor-less), interlaced and binary leaves which transit the fan beam width in about 20 milliseconds
Sinogram	File containing data for each projection. These data may be related to imaging or leaf opening times. For the latter, the sinogram contains the fraction of the time each leaf is open during a projection.
Beamlet	Single beamlet corresponds to the radiation emitted through a single open MLC leaf, with the gantry at any given angle during rotation. It has a width in the transverse direction of approximately 0.6 cm (the projected leaf width) and a length dependent on the jaw setting selected for treatment
Treatment plane	This is the plane through the physical isocentre of the machine perpendicular to the y-axis (inside the bore).
Pitch	Ratio of the couch displacement for one gantry rotation to the slit width.
XML file	XML files are used to transfer all treatment delivery settings of a corresponding treatment plan to the treatment machine.
Output	The dose per unit of time.
Modulation factor	The maximal leaf open time divided by the average of all non-zero opening times. It is a measure of modulation complexity of the treatment.
Cheese phantom	A cylindrical phantom provided by Accuray consisting of Solid Water. The phantom can be used for quality assurance using

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	ionisation chambers and/or film. It is also used to calibrate the Hounsfield units of both the MVCT and the local kVCT unit, and to access contrast and spatial resolution using dedicated plugs.
DQA	Delivery quality assurance: evaluation of the ability of the system to deliver a treatment plan for a patient (=sinogram) correctly. The dose distribution of this sinogram is computed on a new CT study of a phantom, and compared with measurements using this phantom.
Exit detector	A build in, ion chamber based CT detector, mounted at the exit side of the linac, used for CT imaging of the patient and QA applications.
Planned Adaptive	A software package provided by Accuray, to evaluate the impact of daily patient positioning and anatomical changes. The daily delivered dose (verification dose) is calculated on the MVCT images and can be compared to the planned dose.
TQA	Application for automated acquisition and analysis of Tomotherapy Quality Assurance procedures provided by Accuray.
Step wedge	An aluminium phantom to be used in the Step wedge modules of the TQA software
EOP	'End Of Planning' is a dose calculation in full-scatter mode performed after finishing the planning optimization phase.
Gold Standard (GS)	Common beam model shared by all Tomotherapy units
IVDT	Image value-to-density table. Calibration curve for conversion of CT Hounsfield Units to mass density.
Thread effect	Longitudinal oscillations of dose distributions due to helical beam junctioning.
LFOF	Leaf-fluence output factor. Accounts for the change in output for one leaf open, caused by the closed/open state of the adjacent leaves.
JFOF	Jaw-fluence output factor. Accounts for the change in output as function of the jaw size, relative to the 5 cm slit.
Latency	The relationship between the effective leaf open times and programmed leaf open times
Leaf filter	A fluence profile that represents the fluence distribution for a given open/closed leaf configuration
JAM	Part of the machine characterization data that lists the properties of the collimation system

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AOM	Part of the machine characterization data that lists the properties of the beam generating system
statRT	Workflow enabling successively patient imaging, treatment planning and treatment delivery while the patient is lying on the treatment couch.
VoLO	Voxel-less Optimization. New generation of dose calculation algorithm based on GPU architecture.
DMS	Data Management System: application to allow for batch archiving and restoring of patient data and for transferring of patient sinograms to another Tomotherapy system.
T&G effect	Tongue and Groove effect: the leave sides have tongue and groove to limit MLC transmission. Because of this, opening two adjacent leaves simultaneously yields a different fluence from opening them in sequence.
DAS	Data Acquisition system collects and provides health signals of the machine and MVCT exit detector data.
TEMS	Tomotherapy Electrometer Measurement System. Part of the Tomotherapy QA package.
msr field	Machine specific reference field is the static field which is closest to the conventional field size and shape used for dose calibration.
pcsr field	Plan class specific reference field (for dose calibration): a combination of fields in a configuration representing the clinically delivered treatment
DCS	Dose control servo: Automatically output adjusting controls to ensure a stable output. Especially relevant for treatments of longer duration and for treatments with fixed gantry.
TomoDirect	A non-rotational treatment option. TomoDirect allows creation of treatment plans with the use of 2 to 12 target-specific gantry angles. During treatment delivery, all beams for each target are delivered sequentially with the couch passing through the bore at an optimized speed for each individual gantry angle.
DRS	The Data Receiver Server (DRS) converts and stores detector and system data. It is responsible for converting the data such that it can be approached via the ftp standard (File Transfer Protocol)
Medical Physics Expert	(MPE) An individual or, if provided for in national legislation, a group

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	of individuals, having the knowledge, training and experience to act or give advice on matters relating to radiation physics applied to medical exposure, whose competence in this respect is recognised by the competent authority (European Commission, radiation protection no 174, 2014)
IAEA	International Atomic Energy Agency
AAPM	American Association for Physicists in Medicine
NCS	Dutch Commission on Radiation Dosimetry

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1 Introduction

Helical Tomotherapy is an intensity modulated radiation therapy (IMRT) delivery technique combined with an integrated system for image guided radiation therapy (IGRT) using a fan beam megavoltage computed tomography (MVCT) capability.

NCS reports 8 (in Dutch) and 9 (NCS 8, 1995; NCS 9, 1996) are the most recent NCS reports on Quality Control (QC) of Medical Linear Accelerators and are published in 1996. The AAPM Task Group report 142 (Klein et al., 2009) provides QC guidelines for more recent technology. But with the introduction of technology that is different from conventional C-arm type accelerators, these guidelines need to be extended. In 2010 Task Group report 148 (Langen et al., 2010) was published which describes Quality Assurance (QA) guidelines for helical Tomotherapy. It provides a comprehensive set of recommendations on what should be tested and the respective recommended test frequencies. Since then a number of dosimetry audits on Tomotherapy systems have been conducted (Alvarez et al., 2016; De Ost et al., 2011; Duane et al., 2006).

Since publication of TG148 progress has been made on several fields. New dose calibration protocols for non-reference conditions have been developed. The graphical processor unit (GPU) has been introduced as a new hardware platform for dose calculation. The Voxel-Less Optimization (VoLO) dose calculation algorithm was released, subsequently. Treatment delivery with fixed gantry angles (TomoDirect) was introduced based on a new gantry positioning system and gantry drive. Numerous developments made the treatment delivery system more robust and reliable, such as the new High-Precision (HP) couch, the Dose Control System (*DCS*) and the fixed (non-rotating) target. *TQA* was released which offers an integrated tool for QA using the build-in exit detector. TomoEdge allows dynamic jaw movement to sharpen the dose build up cranio-caudal of a target structure.

All this warranted the development of the current NCS report which is a new set of QA guidelines, actualized to the developments made on the Tomotherapy system until mid-2015. These areas of development are basic dosimetry, dose planning, the use of the exit detector for QA purposes, multiple static beam delivery, transfer of patient treatment procedures between Tomotherapy systems and adaptive radiotherapy using the Planned Adaptive application. Other areas are still under development, like dose guided radiotherapy (DGRT) using the exit detector to measure the transmitted fluence through the patient and to reconstruct the fluence applied to the patient. This new functionality is released under the name ‘Delivery Analysis’. It will not be covered in this report.

In 2003 the first Tomotherapy Hi-Art came on the market. In 2010 the Tomotherapy HD was released. In 2017 the Tomotherapy Radixact will be available. In this new design, system

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components have been redistributed to enable mounting of a imaging system. Already released is a fully automated adaptive workflow which uses deformable registration to allow voxel tracking and voxel dose accumulation. Possible future developments such as dynamically tracking of the anatomy and adjusting the leaves accordingly are not dealt with in this report.

All Tomotherapy systems use a factory beam model. Currently two beam models are in production and one legacy model (pre TomoEDGE). Each system is adjusted in the factory such that the beam parameters match one of these models. During on-site commissioning and acceptance testing (ATP), it is verified that this is still the case. A number of ATP tests can be used as reference measurement for regular QA tests. Other QA tests should be performed before the first treatment. It is therefore recommended that a medical physics expert (MPE) on-site is actively involved in the ATP process.

The system was developed at the University of Wisconsin-Madison and was later commercialized by Tomotherapy, Inc., Madison, Wisconsin. In 2011 Tomotherapy, Inc. merged with Accuray Inc., Sunnyvale, California. Accuray is the only vendor that markets and manufactures treatment units that use this delivery process. Procedures and recommendations discussed in this report are therefore specific to Tomotherapy treatment units. The units were introduced into clinical routine in 2003.

In this NCS report, an overview of the Tomotherapy system and its unique aspects is provided. Delivery, imaging and treatment planning quality assurance are discussed. Quality assurance aspects are summarized according to their recommended interval in the appendix. The proposed Intervals for the individual test are defined for a system which is running under a continuous QA-Program and is not showing any systematic deviations. For machines which are newly installed, or show systematic deviations in the tests, the intervals maybe shortened. Additional QA needs to be performed after interventions on the system, including software updates. Which tests are needed should be defined together with the Field Service Engineer (FSE) considering the performed work.

The acceptance test protocol (ATP) and commissioning protocol (CP) are part of the QA program but will not be part of this report.

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2 System overview

Figure 2.1 shows the Tomotherapy system configuration whereas Figure 2.2 shows the general lay-out of the Tomotherapy unit. The 6 MV accelerator is mounted on a slip ring gantry. A flattening filter is not used. The beam is collimated in a fan-beam shape. Time-resolved collimation is provided by a binary multileaf collimator (MLC): each leaf defines a beamlet. The size and shape of each *beamlet* is fixed and the fluence exiting this *beamlet* is either on or off (although the time of flight or *latency* is corrected for during dose calculation). During treatment the couch is translated through the beam plane which rotates continuously (helical mode) or is in fixed positions (static or 'Direct' mode). Opposite the accelerator is a detector array which is used to collect data for MVCT acquisition, for QA purposes and for delivery fluence reconstruction. A beam stopper is used to reduce radiation exposure outside the patient. The distance from the source to the centre of rotation is 85 cm. The source to detector distance is 145 cm. Except for the new 'style 4' detector which is focussed on the source, the detector curvature is focused to a point that does not coincide with the source. This has an impact on the lateral detector response and hence on the measured transversal profile. For such a detector, its profile shows a typical dip in the central part where the rays impinge vertical in the CT detector channels and create less scattered electrons and thus less signal (Balog et al., 2003a). The diameter of the bore is 85 cm.

The fan-beam has a lateral extension of 40 cm at isocentre. In the cranio-caudal, or Y-direction, the beam width is collimated by an adjustable jaw. Three sizes are available: 5 cm, 2.5 cm and 1.0 cm. Asymmetrical adjustment of the beam width is possible and available as the TomoEdge product. This will reduce the dose superior and inferior of the target volume and in between multiple targets which are separated in the sup-inf-direction.

A binary 64 leaf collimator is used to divide the fan beam in the X-direction. The leaves travel cross the fan beam in the Y-direction in an interlaced manner. Leaves with even number are driven from the rear side MLC bank (+Y direction), leaves with uneven number are driven from the front side MLC bank. The leaves are driven pneumatically. This allows a rapid transitioning of a leaf in less than 0.02 sec. Opening and closing of a leaf is controlled around 51 equidistant points every rotation. This space angle of 7.1º is called a 'projection'. The opening of a leaf is always symmetrically around the centre of the projection. The MLC is a binary system, a leaf is either open or closed. During a projection each leaf can be opened once. Intensity modulation is achieved by varying leaf opening time with a minimum of 0.02 sec (typical leaf transit time) and a maximum of 1.176 sec (corresponds to the time to travel a projection using the maximum allowable gantry period of 60 sec).

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Each leaf has a width of 0.625 cm at isocentre. The gantry travels clockwise with constant speed and the angle naming convention is conform to the International Electrotechnical Commission standard, i.e. the gantry angle is zero if the beam points downward in the vertical direction. The treatment plane is inside the bore and for patient set up purposes a virtual isocentre is defined 70 cm outside the bore. A fixed green laser system (outside the bore) is used to project this virtual isocentre with lines in coronal, axial and sagittal orientations. The patient reference point, which is defined during the treatment planning process, is marked on the patient skin. A movable red laser system consists of five units in the room (two coronal, two axial and one sagittal laser). The position of the red laser lines is plan specific and these lines are used to set up the patient using the patient marks.

Radiation delivery is controlled by a custom encoder that is integrated with the gantry to provide angular position information during rotation. This custom encoder is called the ‘tick fence’ and is essentially comprised of a ring of 2880 holes, through which positional signals are received and read by optical sensors. Radiation delivery is terminated after the programmed number of ticks has passed. Treatment plan parameters such as gantry rotation speed and MLC dynamics, but also linac pulse rate and the read out of the build-in exit detector, are all tick-based and synchronized through this tick fence. This removes the possibility for an erroneous variation of dose with gantry angle, when the gantry slows down or speeds up. Couch motion however is controlled fully independently from the tick fence. Counting the number of ticks is equivalent with time only if gantry speed conforms to the programmed value (in seconds). In helical mode the system operates fully in tick domain. In static mode (fixed gantry) the system operates fully in time domain. In static mode gantry positioning is achieved through RSF encoder tape (RSF Inc.) with 550000 counts per 360 degrees.

During beam on, dose rate checks are applied to each of the two monitor chambers independently, such that a dose rate violation detected by either chamber will interlock treatment. The dosimetric effect induced by a dose rate deviation cannot be estimated easily. Due to the sequential nature of dose delivery, only the voxels which are in the beam during this deviation are affected. The effect will also depend on the MLC pattern during this period. The monitor unit (MU) readings that are displayed on the operator screen are derived from the monitor chamber signals. One MU represents the machine output expressed in cGy/min measured at a depth of 1.5 cm with an SAD of 85 cm and a 5x40 cm^2 static field. This MU scaling is performed by the vendor during ATP, using solid water slabs with an insert for an A1Sl ion chamber, and should be approved by the MPE responsible for the machine. The final and determinative dosimetric calibration is performed by measuring, with a calibrated

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ion chamber, a planned dose distribution on a phantom. Initial beam instability is anticipated by closing all MLC leaves the first 10 s of every planned delivery.

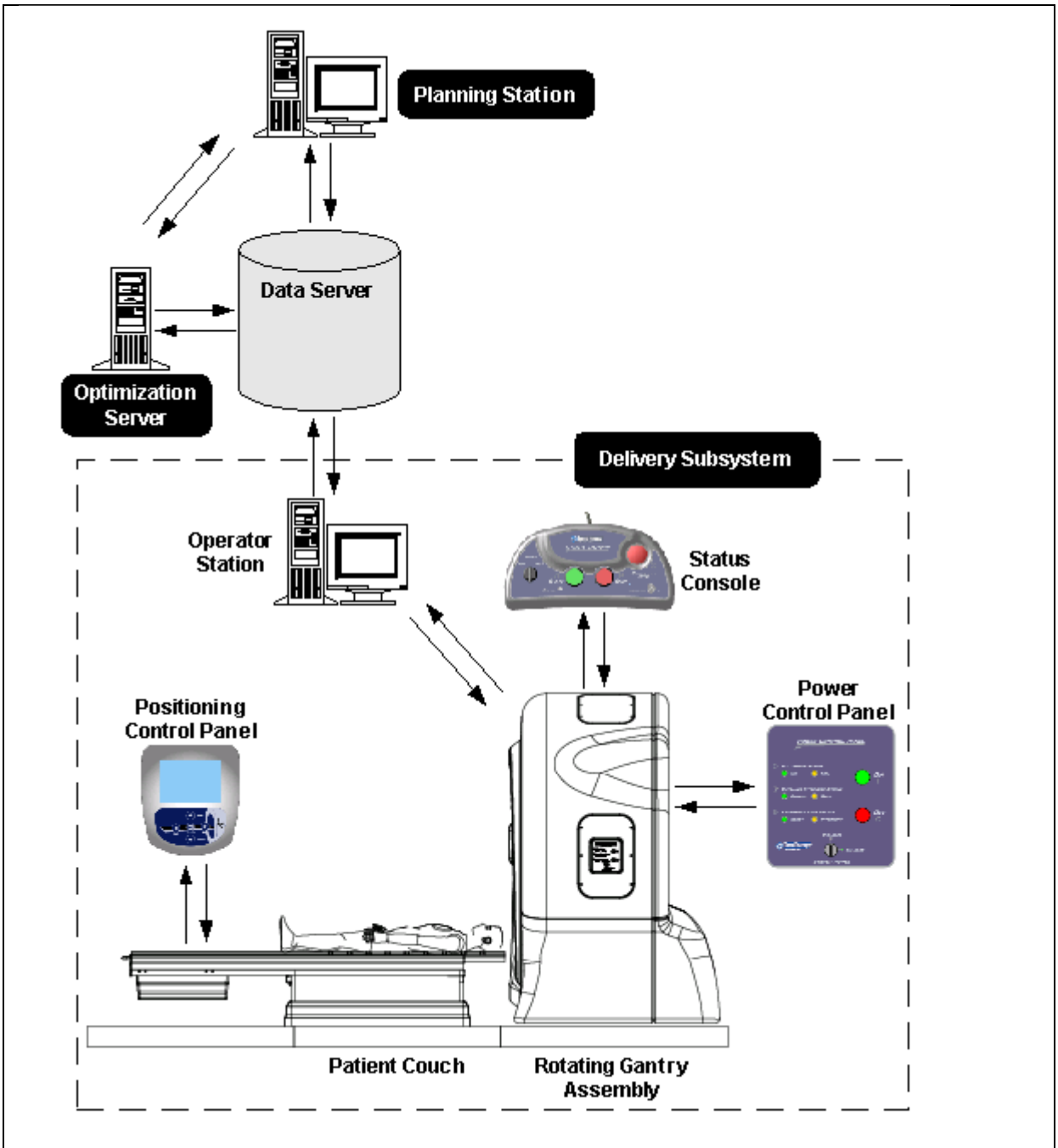

Figure 2.1 Tomotherapy system configuration. More planning stations are allowed. Beside the dose planning it can also support licensed products as DMS, DQA and Planned Adaptive.

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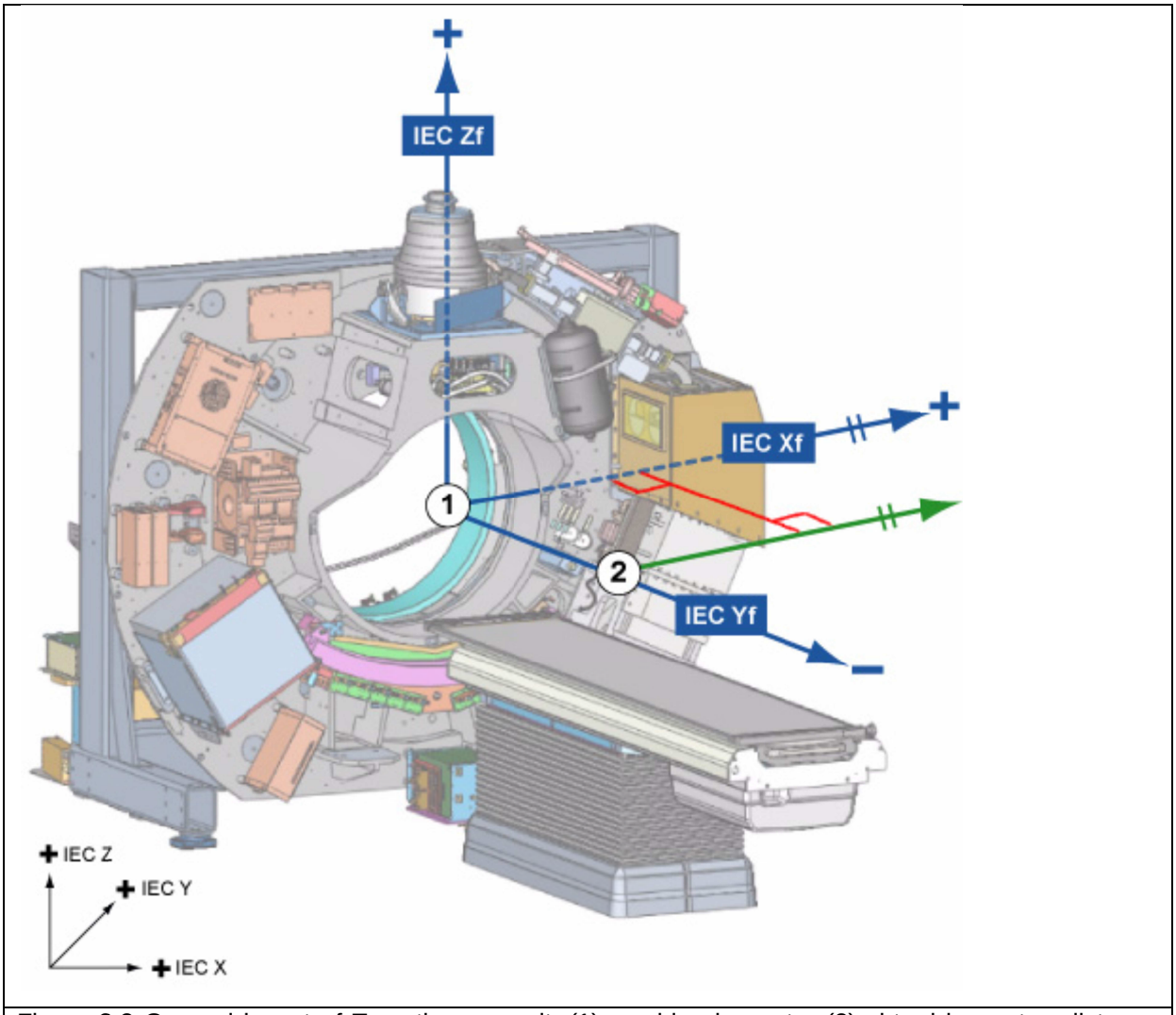

Figure 2.2 General layout of Tomotherapy unit: (1) machine isocentre (2) virtual isocentre, distance between both isocentres is 700 mm. The arrows show the X, Y, Z coordinate convention.

3 Treatment delivery for Tomotherapy

3.1 Introduction

The Tomotherapy beam delivery is unique in combining slip ring technology, binary MLC and moving treatment couch. Therefore, a number of QA tests are Tomotherapy specific. QA items and also the pre-treatment check on a phantom (DQA) can be performed using film, ionisation chamber and arrays of detectors. The latter can be done using devices such as Delta 4 (Feygelman et al., 2010), MapCheck (Jursinic et al., 2010), Tomodose array (Langen et al., 2005b), ArcCheck (Templeton et al., 2015), Octavius (Van Esch et al., 2007) or making

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use of the on-board exit detector (Althof et al., 2012; Balog et al., 2003a; Choi et al., 2014; Van de Vondel et al., 2009). Data from the exit detector are accessible via the Tomotherapy *TQA* application. This application collects detector- and system data by accessing the *DRS* computer in the Tomotherapy machine via FTP. The intent of this chapter is to describe a comprehensive set of QA items, usable for both helical and direct procedures, which need to be addressed periodically to maintain the Tomotherapy delivery system.

3.2 Periodic Quality Assurance

QA tests are described for mechanical alignment, beam parameters, multi leaf collimator properties, miscellaneous aspects and the synchronized dynamic behaviour of gantry, couch and MLC. Quality assurance aspects are summarized according to their recommended interval in the appendix. Measurements and procedures are described in the Accuray user manuals. References are also made to the Task Group 148 report (Langen et al., 2010), which gives a comprehensive overview from the user point of view.

3.2.1 TQA introduction

Tomotherapy Quality Assurance (TQA) is a tool to support a Tomotherapy QA program. The application reads and analyses detector- and system data after a TQA procedure has been run on the machine. TQA consists of several modules to measure various QA items. The tool is intended to monitor changes in system performance that may provide early indications for maintenance or dosimetric validation. TQA is considered as a supplementary quality assurance tool that allows both professionals in the clinic and Accuray Inc. to forecast the need for preventive maintenance before an issue affects the normal functioning of the Tomotherapy Treatment System. Accuray calls this tool ‘supplementary’, because physics quality assurance checks with films and calibrated ionisation chambers remain the primary means of determining the accuracy of the treatment system and the acceptability of a patient treatment procedure. However, for a number of items beside TQA no validated alternative is easily available. This is especially true for dynamic parameters (e.g. MLC properties, cone shape variation per pulse, some dynamic jaw movements) or the behaviour of the detector itself. Moreover, some items need exit detector data to provide data to the beam model (e.g. leaf fluence output factors, leaf latency values, air scan calibration).

Data Acquisition System (DAS)

Most TQA modules make use of data from the built-in exit detector and from system data, which is collected by the Data Acquisition System (DAS). DAS data can only be extracted

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from the system before a new procedure has been selected because this selection will clear the just collected data files. The following TQA modules also use external detectors: ‘Linac Longitudinal Alignment’ and ‘Jaw Sweep’ (A17 ionisation chamber and TEMS software with the Tomo electrometer), and the two modules to measure ‘Field Width’ (fixed and dynamic) using A1Sl ionisation chamber and TEMS software with the Tomo electrometer (Standard Imaging).

A TQA module will process DAS data automatically (auto run). Detector data is extracted from the DAS by FTP. The DAS input files are time-stamped. This time stamp is used to plot data points on the trending graphs. In a manual run, data is submitted by the operator to the TQA server. For off line analysis, the module’s input file can be downloaded from the TQA server and then resubmitted to TQA. The data of a run is stored in an xml output file. This file can be shared with Accuray Inc. for further analysis. The TQA analysis can also be performed on treatment or physics procedures that were delivered without using TQA.

Reference file

Most modules require a reference file to process results. This reference file (*.sig) can be generated by any procedure run. The reference is not created from beam model data (e.g. tabulated MLC latency values) or numerical values (e.g. nominal couch speed). The result of a module run is compared against the reference run of this specific module to produce differential results. These differential results are used to monitor constancy over time. It is important to underline that TQA offers a consistency check only. References can be reset, but to maintain traceability of results and trending data, Accuray Inc. recommend to ‘control’ (to limit) the frequency of replacing a reference by a new one. Before a new reference is set, the user must establish, whenever possible, a direct link between parameters measured using TQA and corresponding physics measurements.

If system properties are out of tolerance, they should be tuned back within specs of the beam model. Only after this procedure, a reference run should be made. This will avoid an unnoticed drift in the values of the QA parameters measured by TQA. If this procedure cannot be followed, it is recommended to keep the first made reference file (closely after ATP or commissioning) on the TQA server. This allows re-analysing TQA data relative to this ‘first time’ reference.

Alert levels

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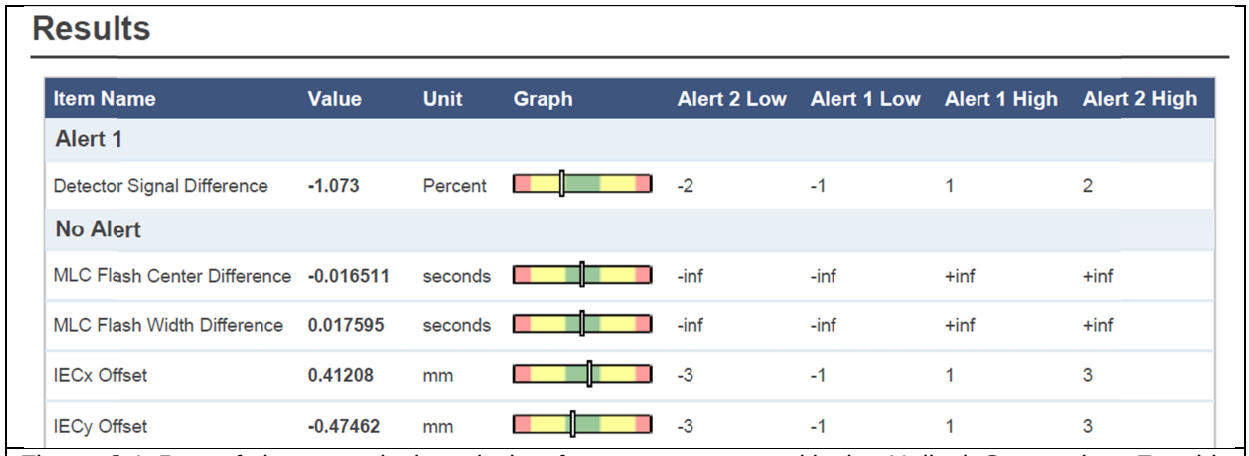
Two alert levels are defined for each item. Alert level 1 indicates that a data item is outside normal operating tolerances and should be monitored, but may not require immediate attention. Alert level 2 indicates that a data item is significantly outside normal operating tolerances and requires immediate attention. The alert levels are set to default values by Accuray Inc. Default alert tolerances may be changed but we recommend to accept the default levels provided by the company. In some instances the default alert levels need reviewing, for example in module 'System Monitor' the responsible field service engineer should review these levels for his specific system. Not all items are provided with alert levels, either because the correct number is not known or the parameter is not suited to be monitored using an alert level. In that case 'inf' could be filled in. The analysis is still performed but without showing alert levels. For some items the authors of the current report recommend alert levels based on their experience and research, as depicted in Figure 3.1.



Results

Item Name	Value	Unit	Graph	Alert 2 Low	Alert 1 Low	Alert 1 High	Alert 2 High
Alert 1							
Detector Signal Difference	**-1.073**	Percent		-2	-1	1	2
No Alert							
MLC Flash Center Difference	**-0.016511**	seconds		-inf	-inf	+inf	+inf
MLC Flash Width Difference	**0.017595**	seconds		-inf	-inf	+inf	+inf
IECx Offset	**0.41208**	mm		-3	-1	1	3
IECy Offset	**-0.47462**	mm		-3	-1	1	3

Figure 3.1 Part of the numerical analysis of a measurement with the Helical Stepwedge. For this particular example the authors suggest to replace the alert levels 1 and 2 for the 'MLC Flash Center Difference' from –inf (=unknown) to 5 and 20 ms respectively.

Alerts generated by TQA should NOT be viewed as an indication that the system does not function. TQA enables proactive diagnosis of system health before downtime occurs. Because a TQA measurement is easily performed and automatically analyzed, TQA tends to increase the frequency of QA checks. Moreover, any TQA module incorporates several tests at once, not all of them necessarily have to be measured with the same frequency.

The user can design his own measurement schedule in TQA (Daily, Weekly, Monthly and Annually or event driven (post-service checks or other events)).

No data is provided by Accuray Inc. on the sensitivity, reproducibility and accuracy of the TQA tool. Accuray warns against misinterpretation of the results. For instance cone shape is sensitive for a change in energy, but this may not be the only cause. In this example, the

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MPE should always perform ionisation chamber measurements at different depths in water (-equivalent material) to confirm TQA results. Furthermore, as an example, because TQA analysis of beam energy is based on comparison of measured attenuation profiles of the step wedge phantom, a large set-up error of the phantom on the couch will cause not only an alert violation on translation, but also on the attenuation profile.

Althof et al (Althof et al., 2012) present an in-house developed analysis tool using the same static Stepwedge phantom procedure as TQA. A comparison is made to standard physical measurements using ionisation chamber and film which showed that the static Stepwedge procedure is an accurate and effective tool for QA measurements.

For detailed information about the algorithms used for analysis of the TQA data see the TQA manual.

Tick fence

The tick fence is a delivery safety system, as briefly mentioned in chapter 2. Leaf modulation, linac pulse rate and on-board exit detector read-out, are all synchronized with gantry position. The tick fence imposes implications on the interpretation of measurements performed in helical mode using the exit detector. In fact, variations in gantry period cannot be measured by the Stepwedge Helical module (see paragraph 3.2.2) because a gantry that rotates faster, will also speed up the sampling of the exit detector by the same amount. As a result, the gantry movement is presented as being constant, provided the tick fence works correctly. Therefore, a variation in the QA item ‘gantry period difference’, is not an indication about gantry behaviour, but it points towards a failure of the tick fence system, which is valuable in itself.

Some QA parameters measured in helical mode are presented in the TQA analysis in units of time. In fact this is incorrect. This should be interpreted as units of ticks, which can be converted to time, assuming a constant tick/sample ratio. This is only correct if the gantry speed is constant.

Because couch speed is not controlled within the tick fence system, it would be useful to have a method to measure synchronicity between gantry and couch. Of course there are secondary build-in system checks and interlocks on couch speed and position.

3.2.2 TQA module description

This paragraph lists all available TQA modules. Each module is characterized by: Purpose, Set up, Parameters, Interval and Description. A complete overview of all QA items (including

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TQA) with measurement frequencies, parameters and tolerances (alert levels), is given in the tables in the appendix.

TQA module: Basic dosimetry

Purpose: Rotational Variation (RotVar) procedure, no absorber in the beam. It measures and analyses the signal of monitor chamber 1 (MC1), the exit detector output (central channel) and the transversal profile (cone shape; all detector channels).

Set up: No absorber in the beam path

Parameters: All leaves open, 1 cm slit (J7), sample rate is 33.3 ms (sampling at 300 Hz with a compression factor 10). Beam on time is 200 sec, gives a total of 6000 pulses. Estimated time to complete the procedure, including the analysis of the results, is 10 min.

Interval: Daily

Description: raw and normalized detector signal of the central channels and monitor chamber 1 (MC1) output, output ramp up (number of pulses to reach the average output level), exit detector cone profile, gamma index (comparison normalized 'just measured' cone profile versus normalized reference cone profile), pulse by pulse showing MC1 and cone shape variation. If monitor chamber data does not match exit detector output, there may be an issue with dose monitors, energy, target condition, jaw collimation or the detector array. The sensitivity of the exit detector channels may decrease up to 2.5%/year (depends on detector type). Therefore the ratio 'exit detector average to Dose1' will drift accordingly.

TQA module: System monitor

Purpose: To evaluate overall technical system performance using any XRT procedure type, including a patient treatment. This TQA module is recommended on a daily basis for instance together with the TQA module Basic Dosimetry. It can be applied on an ad-hoc basis (in case of acute problems in system performance).

Parameters: The analysis includes health signals like system temperature, flow meter data, water and air pressure etc. These monitored items do not represent calibrated, traceable measurements. Tolerances are set by the vendor, and it is recommended to adhere to these.

Interval: Daily

TQA module: Air scan

Purpose: Is recommended to perform daily and is used for two purposes. First, to normalize detector data in the image reconstruction process to ensure MVCT image quality (Monitor

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Chamber 1 offset and Exit Detector signal offset average). Secondly to evaluate rotational jaw stability to detect hardware degradation of the collimation system.

Set up: No absorber in the beam path

Parameters: Jaw position variations can be inferred from MC1 and exit detector data and are analysed in three sections of the detector array. The result is depicted as the 'Peak to Peak Fluence Variation' (mm). Jaws are set to the imaging beam size (J1 or J4).

Interval: Daily

Description: All leaves open, 6 gantry rotations (10 sec per rotation), raw data, and no absorber in the beam.

TQA module: Daily QA

Purpose: A compilation of tests from other modules. Provides an overall assessment of system health. A 300 sec procedure with no data compression (raw data).

Set up: No absorber in the beam path

Interval: Weekly - although a daily run does not increase workload significantly, a weekly frequency is found adequate looking at the type of tests performed in this module.

Description:

DQ/RotVar as in module Basic Dosimetry, but with the 5 cm slit (J48), 10 sec gantry, 8 rotations, all leaves open. Gives information on signals from MC1 and exit detector (central channels and cone shape).

DQ/RotVar with the imaging beam jaw setting (J1) but with the treatment beam AOM settings. Analysis as in Basic Dosimetry.

DQ/RotVar with the 1 cm slit (J7). Analysis as in Basic Dosimetry.

DQ/'Linac transverse alignment', as in the module with this name but in less time. Uses Tongue & Groove to analyse the transverse alignment of the linac compared to the collimation system.

DQ/Y-axis and exit detector alignment: This part of the module assumes the detector is rigidly attached to the gantry drum. The detector output ratio is calculated for two half open 5 cm fields. One field has a front jaw setting of -2.4 and a back jaw setting of 0. The other field has a front jaw setting of 0 and a back jaw setting of 2.4. The output ratio of detector channels for both jaw settings, calculated at three positions (far left versus far right, and centre) should be within a given tolerance. The difference between far left and far right is also a measurement of jaw twist.

Once a reference data set is established, any change may indicate a change in jaw position or in beam coincidence with the axis of gantry rotation. This module does not replace the film

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procedure ‘Y-Axis beam centring and alignment (section 3.2.3)’, but can be used as a constancy tool for this parameter.

DQ/Dynamic Jaw Sweep: Measures the dynamic behaviour of the jaws. With one jaw parked at maximum extended position, the other jaw quickly sweeps across its range (and vice versa). The jaw position is monitored every 2 ms and then compared to the expected position on the OBC every 100 ms. The data is plotted against time. The location of the 50% profile value is determined and compared to reference data. Also the variability in slit size is trended (max back/front jaw encoder error).

DQ/Leaf Latency: is a measure of MLC dynamics using two slit sizes (J7 and J20). A group of 8 leaves is opened/closed during different fractions of the projection time. A time analysis of leaf movement is made using the raw detector data (3 ms time resolution).

DQ/All leaf latency is a test of adequate air pressure under maximum demand on the air supply.

TQA module: Stepwedge static

Purpose: Monitors output, jaw collimation, couch speed, green laser alignment, beam energy spectrum consistency, detector response consistency.

Parameters: Gantry at zero degrees, all leaves open, no modulation. Slit size 1 cm, couch speed 1.5 mm/sec, 220 sec beam on, compression factor 10.

Set up: Stepwedge phantom is aligned at the green lasers on the couch with the steps facing the gantry. See figure 3.2.

Interval: Weekly

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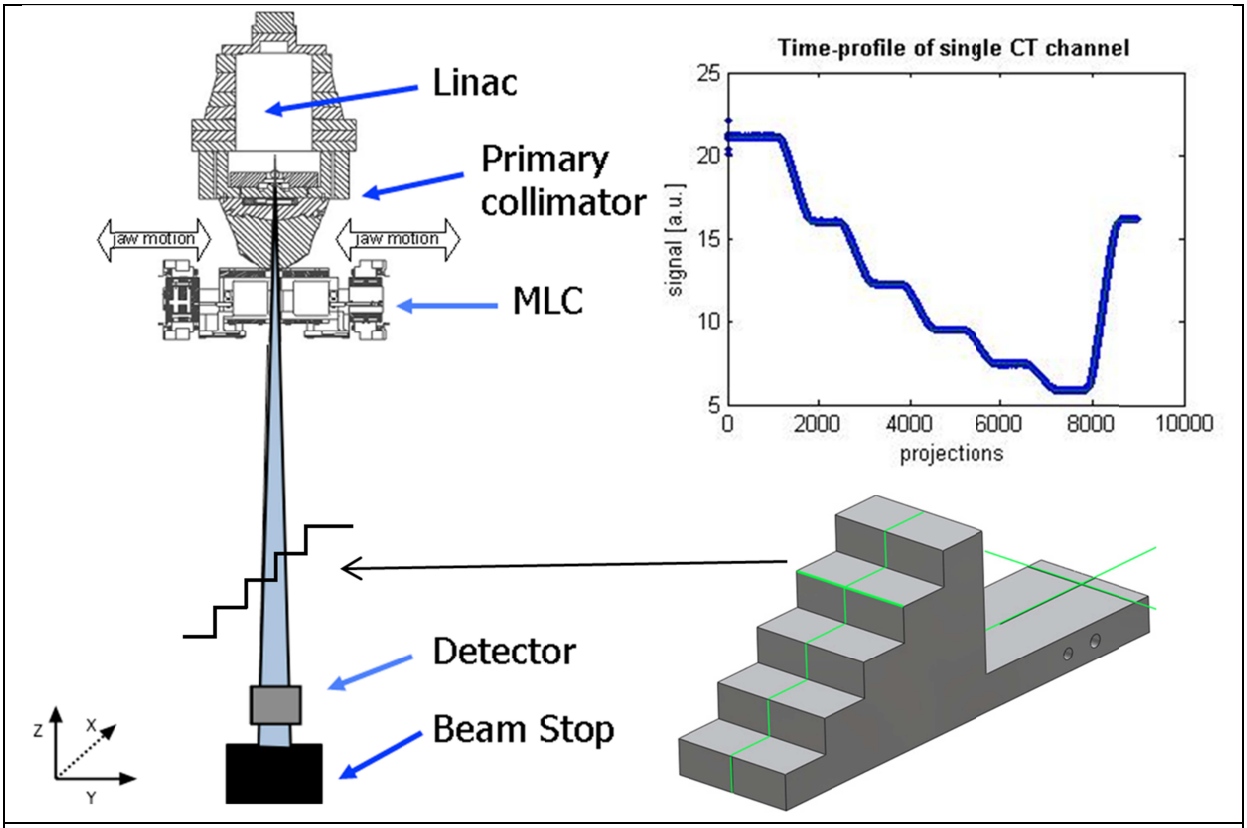

Figure 3.2 Measurement set up of the stepwedge and the measured stepwedge time profile

Description: The Step wedge is positioned on the couch according to the green lasers (these lasers are fixed in space and define the virtual isocenter. See also chapter 2: 'System Overview'). Each average of 10 detector read outs provides an image of the Stepwedge profile subtracted from the open beam cone profile. The position of the centre of this Step wedge image provides a measure of lateral position consistency (IECx) of the green lasers, the width of the image provides vertical position consistency (IECz). The location of the step gradient centres provides a longitudinal position consistency (IECy). The distance between the half-value locations between each step quantifies couch speed. Because the system does not rotate, the tick fence is not used and the couch speed is measured in time domain. The Edge slope Average Ratio measures the slope of the step edges. This is correlated with field width. If the step wedge is not set up at the same height as the reference, procedure results may imply that the field width is off.

The slope of the attenuation (measured by analysis of the step profile) is determined to check energy constancy. Energy difference is calculated by comparing the slope of a linear fit through the natural log of the step wedge profile data with a reference slope (Figure 3.3).

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An ionisation chamber may be inserted into the base of the step wedge to measure dose. These data are not analysed by this module.

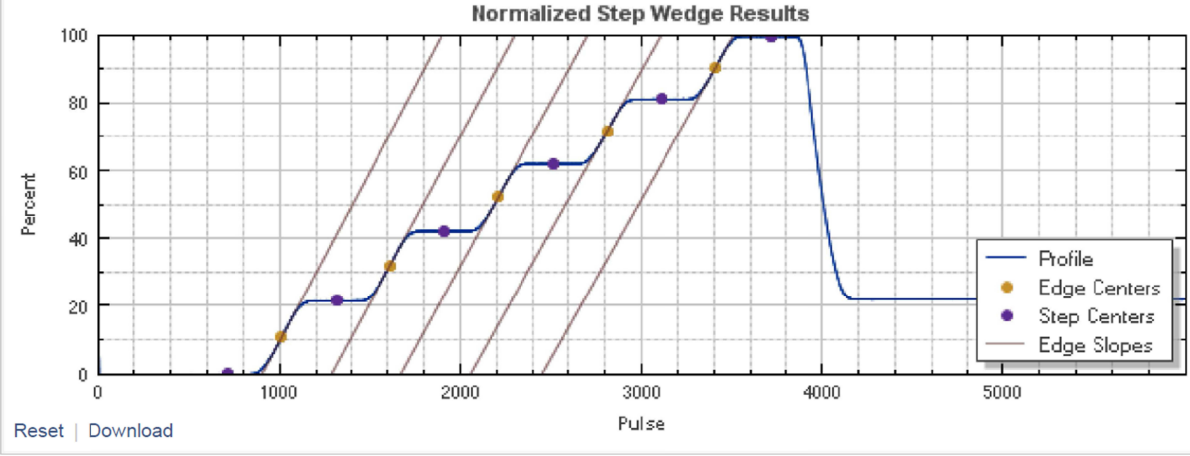

Figure 3.3 The static stepwedge time profile reflects the attenuation of the stepwedge levels, measured with the on board exit detector.

TQA module: Stepwedge Helical

Purpose: It monitors output, jaw collimation, green laser alignment, beam energy spectrum consistency, detector response, gantry position (the phase), gantry period and timing of MLC open/close.

Parameters: Field width 1 cm, couch speed 1.0 mm/sec, modulated leaf motion, 200 sec beam on, gantry period 20 sec, nr rotations 10, compression factor 10.

Set up: Stepwedge phantom is aligned at the green lasers on the couch with the steps facing the gantry

Interval: Weekly

Description: Attenuation profiles are (periodically) unique at a given gantry angle. Comparison of (the position of the center of) the attenuation profiles with reference profiles (the 'step center'), forms the basis of this TQA analysis.

Variation in gantry phase angle around the levels of the stepwedge, may point towards a mismatch between couch and gantry position.

Note 1: The Stepwedge Helical module does not provide metrics about gantry period differences, in the case of a correct functioning of the tick fence. See the item 'Tick fence' in paragraph 3.2.1. Report TG148 (paragraph V.B.3) describes a synchronicity measurement between leave motion and gantry position, and between couch and gantry position, using film. See also this report, paragraph 3.2.6. A combined measurement of synchronicity

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between couch, leaf and gantry could in principle be performed with an 3D detector array like ArcCheck (Sun Nuclear).

Note 2: 'MLC flash centre' and 'MLC flash width' are presented in msec. Strictly speaking, this is incorrect and should be given in unit of ticks. Implicitly it is assumed that ticks and time are equivalent. Such equivalence assumes a correct and constant gantry speed. Please refer to the item 'Tick fence' in paragraph 3.2.1.

Note 3: The slope of the attenuation, as measured by analysis of the step profile, is determined to check energy stability. However, the result of this analysis depends heavily on set up variations of the phantom, couch and gantry speed and signal variation by couch absorption. It is therefore recommended to measure beam energy constancy with the static Stepwedge module.

Note 4: If the tick fence fails, the gantry position and timing of leaf motion will be incorrect. The tick fence consists of 2880 ticks, which is 8 ticks/degree. This committee advises to use an alert of 1º in gantry angle difference when using the Step wedge helical module (10 rotations) which corresponds to a tick counting error of, on average, 0.8 tick/rotation.

TQA module: Linac longitudinal alignment

Purpose: This TQA module tests the alignment of the linac photon source in relation to the jaw collimation in IEC y.

Detector: Ion chamber with a long active volume and a homogenous response. The vendor recommends the Exradin A17.

Set up: The long axis of the ionisation chamber is positioned along the Y direction.

Interval: After replacing or disturbing any component that may affect this alignment. Otherwise annually.

Tolerance: The source position should agree with its nominal position (established at factory commissioning) within 0.2 mm for a TomoEdge system and 0.3 mm for a non-edge system (vendor's specification).

Parameters: The test involves comparing ionisation chamber measurements (A17 ionisation chamber) at machine isocentre for different jaw settings.

Description: The slit has an opening of 2 mm that is centred over different positions along the longitudinal (IEC Y) axis. By using an ionisation chamber with a uniform response over a long collection volume, the chamber does not have to be moved between procedures. The chamber signal is plotted as a function of axial jaw shift. When the source is aligned with the y-jaw, the maximum output should be observed at zero jaw shift, and output should fall off

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equally on either side. The signal peak is determined by a parabolic fit to the data. An example data set from this procedure is shown in Figure 3.4.

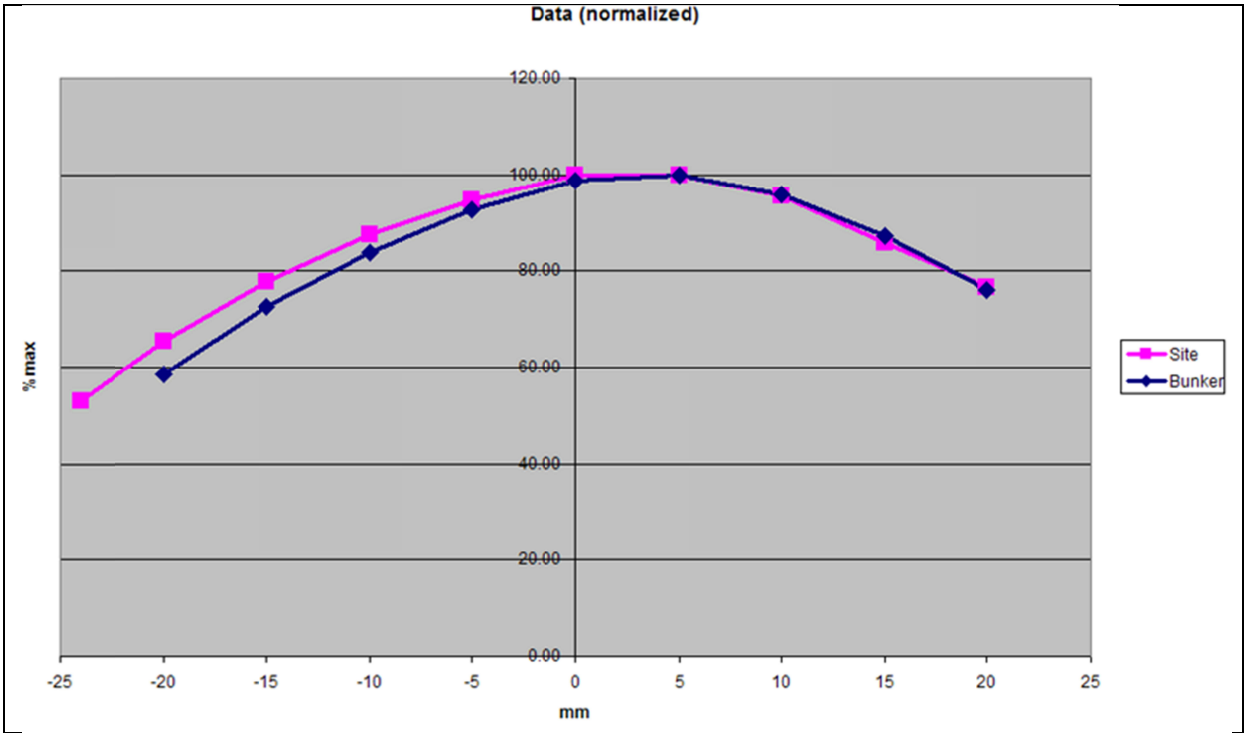

Figure 3.4 The response of the ionisation chamber as function of the longitudinal position of a small 2mm slit relative to the source. Analysis may show a difference in source position relative to the commissioned factory situation, revealing a necessary jaw actuator shift.

TQA module: Linac Transverse Alignment

Purpose: This TQA module tests the alignment of the linac photon source with respect to the MLC in the lateral (IEC X) direction.

Set up: No absorbers in the beam path

Interval: After replacing or disturbing any component that may affect this alignment is replaced or moved. Otherwise annually.

Tolerance: out-of-focus within 2% which corresponds to a source position offset of 0.34 mm (Langen et al., 2010).

Description: The centring of the radiation source in x is measured using the Tongue and Groove (T&G) effect. This effect is caused by the T&G design of the leaves that prevents a direct path for radiation to pass through when adjacent leaves are closed. A consequence of this design is a difference in fluence if two adjacent leaves open in sequence or simultaneously. The T&G effect is most symmetrical if the MLC is focused to the source in

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the x direction. The exit detector array is used to collect output profiles with all even-numbered MLC leaves opened and subsequently with all odd-numbered MLC leaves opened. This delivery sequence will maximize the T&G effect. The TQA application will add the odd-numbered leaf profiles and even-numbered leaf profiles and divide the result by an output profile that is collected with all MLC leaves open. This normalized T&G profile should be symmetric about the centre if the source is properly aligned with the MLC. Figure 3.5 shows normalized T&G data. An 'out-of focus' value is calculated based on the right-left asymmetry of the profile. The result of this calculation is presented in % out-of-focus. For the exact formula see the Accuray TQA manual or TG148 (Langen et al., 2010).

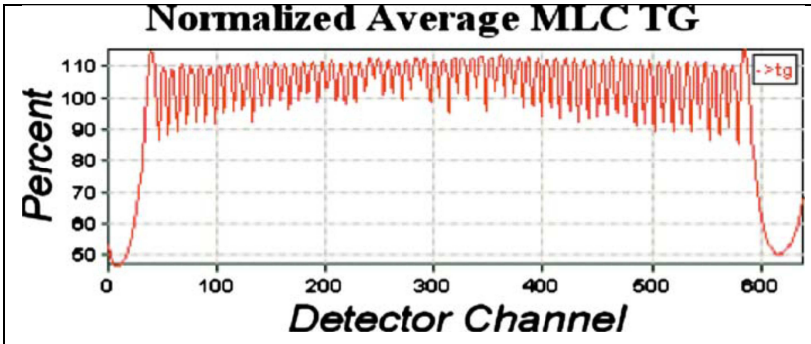

Figure 3.5 Normalized tongue and groove data to analyze the alignment of the photon source in the lateral (IECX) direction. Measured with the TQA module 'Linac Transverse Alignment'.

TQA module: Jaw Sweep (dynamic jaws)

Purpose: This module tests the movement of the dynamic jaws, the jaw fluence output factors and the alignment of the linac photon source in relation to jaw collimation (as in module 'Linac longitudinal alignment).

Detector: A17 ionisation chamber and TEMS electrometer

Set up: Position the long axis of the A17 in the Y direction, with the triaxial cable facing away from the gantry. Setup the correct in/out and height position.

Parameters: Beam on time is 600 sec, couch and gantry are static, all leaves open.

Interval: weekly

Description: Jaw fluence output factors are measured for 4 slit widths: J2, J7, J14 (in between, non-clinical width) and the J20. Back and front jaw sweep measures the fluence profile of an individual jaw as it opens and closes. Symmetric open/close measures the same for simultaneously opened back and front jaws. Time skew measures the variation in position in time when the jaws are opened and closed quickly. The differences in the detector signal time profile to a reference profile is shown and should be monitored (See **Figure** 3.6**).**

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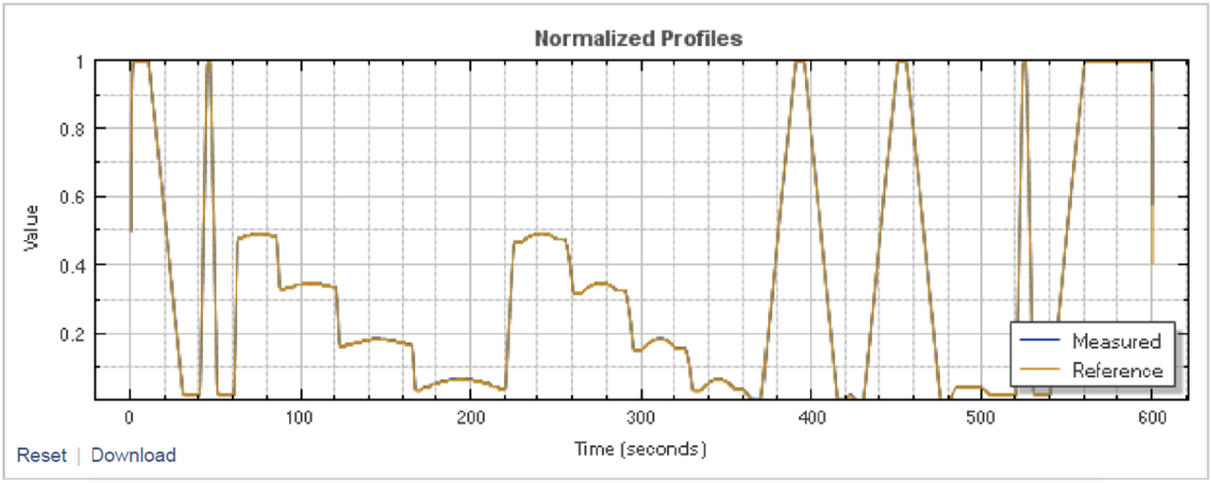

Figure 3.6 Graphical result of the TQA module 'Jaw Sweep'. Several jaw sweep patterns are measured for 4 slit widths. The measured profiles overlap the reference profiles.

TQA module: Field width (fixed jaws)

Purpose: Measurement of longitudinal field size and shape for all clinical slit widths.

Detector: A1Sl ionization chamber and TEMS electrometer

Set up: A solid water slab is positioned on the couch with the long axis in the Y direction. The A1Sl is inserted and a 0.5 cm slab of solid water is positioned on top of this configuration.

Parameters: All leaves open, couch 1 mm/sec, 200 sec beam on.

Tolerance: 1%

Interval: Monthly

Description: Topographic procedure: An A1SL chamber is positioned in the slabs at depth of 1.5 cm, with the chamber axis parallel with the plane of rotation. The beam profile is collected by the TEMS. The field width is determined at FWHM. The difference to the reference is converted to jaw encoder units to assist adjustment of the machine collimation system. This procedure can be omitted when the 'Field width – dynamic jaws' is performed.

TQA module: Field width (dynamic jaws)

Purpose: Measurement longitudinal field size and shape for a number of symmetric and asymmetric slit widths.

Detector: A1Sl ionization chamber and TEMS electrometer

Set up: A solid water slab is positioned on the couch with the long axis in the Y direction. The A1Sl is inserted and a 0.5 cm slab of solid water is positioned on top of this configuration.

Parameters: All leaves open, couch 1 mm/sec, 720 sec beam on.

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Tolerance: 1%

Interval: Monthly

Description: The same procedure as with the fixed jaws. The number of commissioned field widths has increased from 3 to 10. Beside the symmetric fields also a number of asymmetric fields are measured. See Figure 3.7.

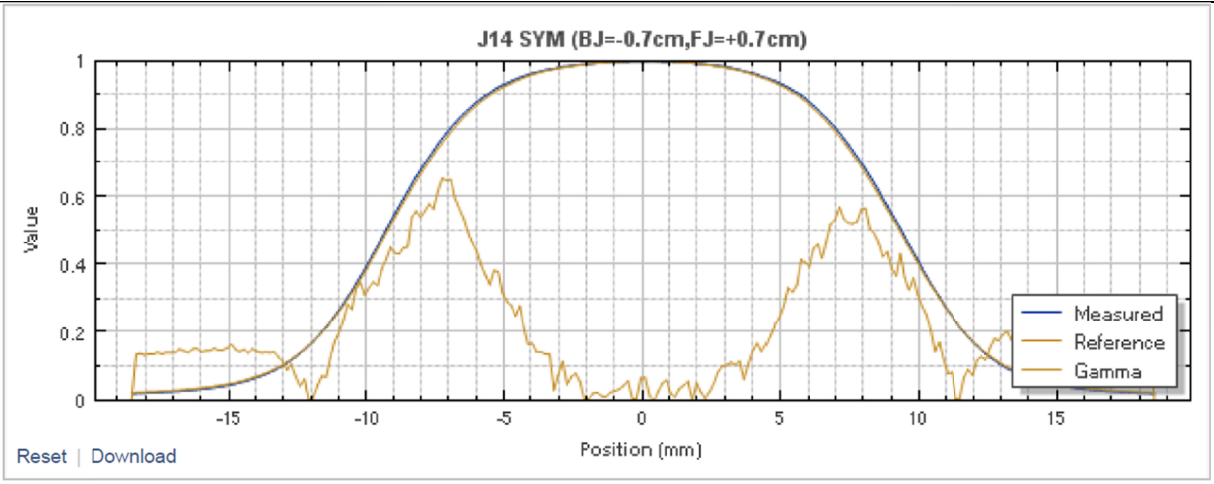

Figure 3.7 Gamma analysis of the J14 topographic profile. Measured with the TQA module Dynamic Field Width, using an ionisation chamber.

3.2.3 *Mechanical alignments*

This paragraph describes measurements of QA items covering beam alignment, beam properties and output.

Alignment source in Y

Measurement procedure is described in section 3.2.2, TQA module ‘Linac longitudinal alignment’.

Alignment source in X

Measurement procedure is described in section 3.2.2, TQA module ‘Linac transverse alignment’.

Y-Axis beam centring and alignment Procedure

Purpose: The alignment procedure of the y-jaw with the beam plane assures that the central beam axis intersects the rotational axis perpendicularly, that the beam diverges symmetrically around the plane of the gantry rotation and that there is no rotation of the jaw

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around a vertical axis (twist).

Detector: film, CT detector

Set up: film on couch, couch is fixed in height, couch is not in isocentre, irradiated from 0° and 180°

Interval: After replacing or disturbing any component that may affect this alignment is replaced or moved. Otherwise annually.

Tolerance: The deviation of the beam axis from perpendicular at isocentre should be 0.5 mm or less. The jaw twist should be less than 0.5° (vendor's specification).

Description: A filmless alternative using the exit detector is available in TQA module 'Daily QA': the 'Y-jaw and exit detector alignment'. The reference for this filmless TQA procedure should be acquired in the same measurement session as the film procedure described in this section.

A film is positioned horizontally between solid water plates (depth of 2 cm) and is positioned below the isocentre (as far as possible to increase sensitivity). The isocentre is defined by the stationary green lasers. The Y-collimation is set to a nominal clinical field and the gantry is positioned at 0°. The MLC field is defined such that only leaves at one lateral side of the central axis are open during exposure. After the first irradiation, the gantry is rotated 180° and a second irradiation is delivered using the same treatment slit width and MLC configuration. Figure 3.8 illustrates this test procedure. To verify that the beam divergence is centred on the plane of gantry rotation, the centre of both fields is measured, using film analysis QA package RITg148 from RIT Inc. The position of the linac in Y direction and the CAX-Y result from this analysis, are related by a ratio of 18. For example, with a film located 25 cm below isocentre, a 0.3 mm difference between the beam centres on the film would translate into a beam divergence at isocentre of 0.51 mm.

Offset tolerance is ±0.5 mm and ±0.1 mm when the 'Central Axis Y-axis Misalignment Procedure' is used as the measurement to establish a reference for the TQA module 'daily QA'.

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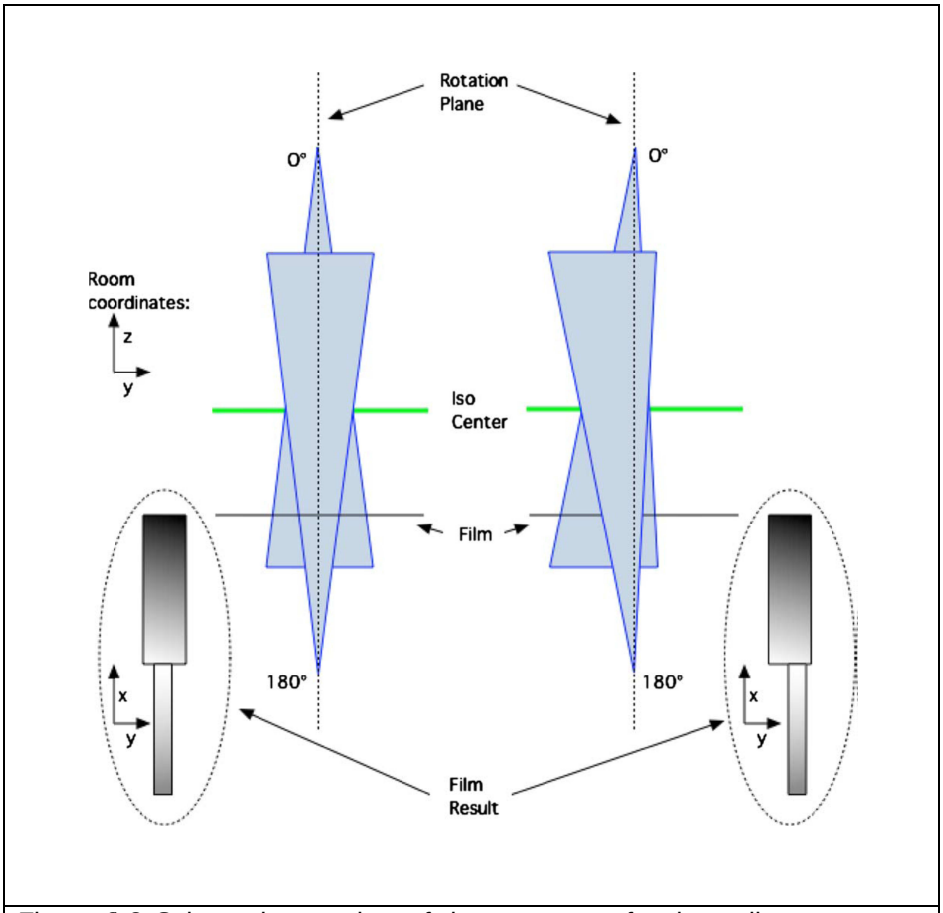

Figure 3.8 Schematic overview of the test setup for the y-divergence test with a schematic of a the film results. In the picture on the right hand side, the beam does not diverge symmetrically to the axis of rotation. This situation would require an adjustment of the jaw encoders. (courtesy of TG148 report on Tomotherapy Quality Assurance)

The jaw twist is measured on the same film. The centre lines of both profiles are detected.

The half of the slope between both centre lines equals the physical jaw twist. See Figure 3.9.

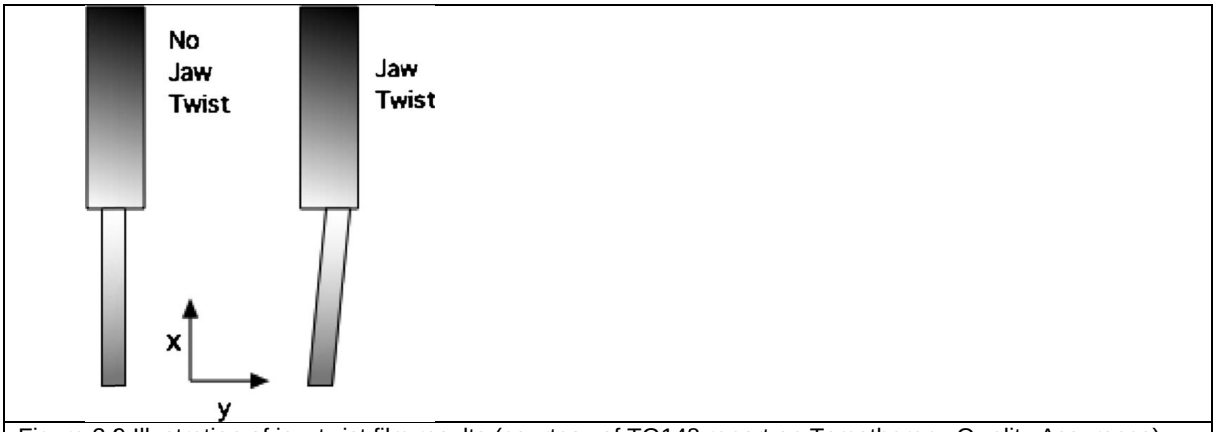

Figure 3.9 Illustration of jaw twist film results (courtesy of TG148 report on Tomotherapy Quality Assurance)

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Treatment field centring

Purpose: To measure the coincidence of the centre positions of the available field widths

Detector: film

Set up: perpendicular to beam axis, in isocentre, build up, gantry at 0°

Interval: After replacing or disturbing any component that may affect this alignment is replaced or moved or on other indications.

Tolerance: Field centres should agree within 0.5 mm at isocentre (vendor's specification).

Description: Two y-jaw widths at a time can be checked on the same film. As an example see Figure 3.10: the leaf pattern is such that for jaw width 2.5 cm 3 blocks of each 7 leaves are opened and for jaw width 5 cm four blocks or each 7 leaves open. The film is irradiated with both leaf settings. From the profiles the field centres for both jaw widths can be analysed.

Figure 3.10 Film for test of clinical beam axial centring. (courtesy of TG148 report on Tomotherapy Quality Assurance)

MLC alignment: position and orientation of leaf bank relative to centre of rotation

Detector: film

Set up: perpendicular to beam axis, in isocentre, gantry at 0° and 180°

Interval: After replacing or disturbing any component that may affect this alignment is replaced or moved. Otherwise on indication.

Tolerance: MLC lateral offset less than 1.5 mm and twist less than 0.5° (vendor's specification). The value of the lateral offset is taken into account during planning.

Description: This test checks the lateral alignment of the MLC bank relative to the centre of rotation. Two paired central MLC leaves and two paired off centre leaves are opened. Film is exposed at 0°. Gantry is rotated to 180°. Now only the paired off centre leaves are opened. The result should resemble the image shown in Figure 3.1. The central exposed area should be centred between both outer areas. Both outer areas should be parallel. Offset and twist measured from the film is magnified by a factor of 2, because misalignments are added from each of the two exposures. The results should therefore be divided by 2.

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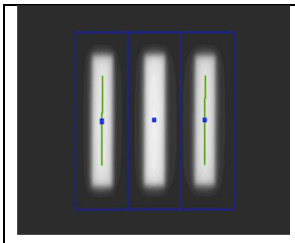

Figure 3.11 MLC alignment/twist test. (courtesy of TG148 report on Tomotherapy Quality Assurance)

3.2.4 Beam parameters

Beam energy - PDD

Detector: (1) ionisation chambers (2) on board exit detector

Set up: (1) solid water slabs and two ionisation chambers in 10 and 20 cm depth (2) TQA with Stepwedge static

Interval: weekly

Tolerance: 2%

Note: The reference for any field measurement of beam quality, should reference to a corresponding measurement in water. This water PDD should be within specs of the PDD used in the beam model.

Description: Two methods are described to perform a field measurement. (1) Point measurements in water equivalent material at two depths 10 and 20 cm (solid water slabs are part of the QA package of the vendor) and (2) using the TQA Stepwedge static module, beam quality is monitored by measuring a (derivate of) the PDD curve. The TQA module Stepwedge Helical is not suited to measure the energy accurately but it can be used as a tripwire. The Stepwedge Static module measures the beam attenuation with filters of different effective thickness (the levels of the Stepwedge) pushed through the beam by the moving couch. The on-board exit detector detects the transmitted fluence. From the Stepwedge measurement a PDD20/10 value is obtained. In TG-142 (Klein et al., 2009) the tolerance for beam quality variations is 1% for the PDD20/10 and the recommended interval of beam quality test should be monthly. In NCS 9 (NCS 9, 1996) the tolerance is 1% and the interval is annually. For the Tomotherapy system using a rotating target (Siemens linac) an increased tolerance value of 2% for the PDD20/10 and a weekly measurement is recommended because of beam quality changes that occur due to target wear (Althof et al., 2012; Staton et al., 2009). Staton found dose deviations between planned and delivered treatment up to 4.5% due to target wear. The rotating targets are being replaced in the field by non-rotating targets which are much less sensitive for target wear. The TG-142 tolerance of 1% for the PDD20/10 for beam quality variations is recommended for these non-rotating targets.

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Only if a rotating target is in use, it may be necessary to tune beam quality over time. This adjustment can only be done within a limited range, making timely replacement of this type of target recommended. Trends in PDD ratio allow predicting target replacement. Kampfer (Kampfer et al., 2011) suggests performing target replacement if the PDD20/10 has drifted by 1.5% to a lower value. Althof (Althof et al., 2012) shows that in the DQA procedure of a helical treatment a 2% change in PDD results in on average 3% difference in measured and planned point dose, measured on a high dose, low dose gradient position. It is expected that the TomoDirect technique, using a limited number of beam directions, is more sensitive on changes in beam energy spectrum.

On an annual basis, agreement with the beam model should be verified for each commissioned treatment slit width by measuring the PDD in a water tank.

Cone (Transverse) beam profile

Detector: exit detector or ionisation chamber

Set up: TQA (no absorber) or water tank measurement

Interval: TQA daily and water tank annually

Tolerance: 2%

Description: By design Tomotherapy units are not equipped with a flattening filter and the transverse beam profiles are cone shaped. TG-142 (Klein et al., 2009) specifies a beam profile consistency tolerance of 1% for monthly beam profile tests, measured within 80% of the transverse field size. Cone profiles are monitored in several TQA modules using the on-board exit detector. Because exit detector efficiency changes with off-axis distance, the detector data are not used to measure the shape of the beam profile as it is used in the beam model, but to test its consistency to a reference. Inherent to the use of the on-board exit detector system is the assumption that the off-axis detector response remains constant over time. Althof et al (Althof et al., 2012) reports 3 year trend data from two Hi-Art machines. A decrease in sensitivity relative to the monitor chamber up to 2.5% per year for the central channel was reported. No data was available for the other detector channels. However, the trend data did not show profile changes that could not be explained by target wear or failure of a specific channel. The exit detector profiles should be referenced to water tank profiles annually.

Longitudinal beam profiles

Detector: ionisation chamber

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Set up: TQA modules Field Width (static, dynamic): profile with solid water slabs and A1SL ionisation chamber. Water tank, set up the same as during commissioning. See Figure 3.12.
Interval: TQA Field Width: monthly. Water tank: annually
Tolerance: 1% in FWHM, gamma analysis on profiles

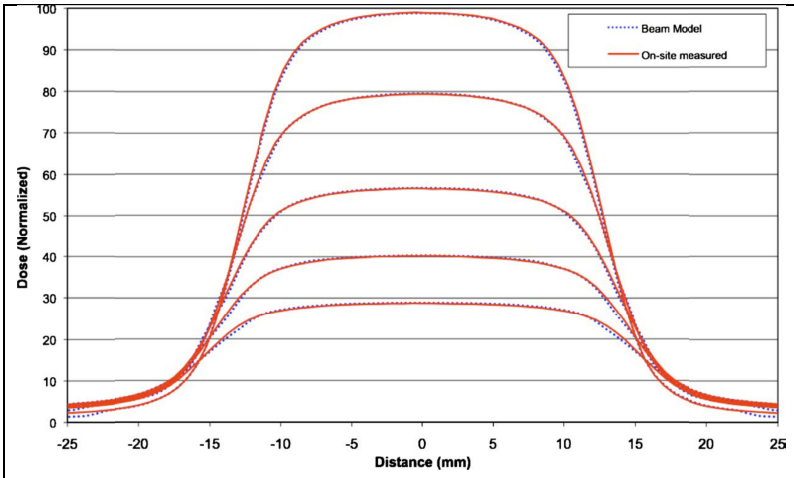

Figure 3.12 Example of longitudinal beam profiles measured in a water tank and the respective modeled beam profiles. Data were acquired at an SSD of 85 cm and at depths of 15, 50, 100, 150, and 200 mm. (courtesy of TG148 report on Tomotherapy Quality Assurance)

Description: The constancy of the longitudinal profile shape and size is particularly important for helical Tomotherapy. The dose to the patient is the integration of the longitudinal profile with couch motion (Balog et al., 2003b). Typically, the dose delivered will change approximately ± 2% if the nominal 10 mm field width changes by 2%. Monitoring of the beam's FWHM is therefore recommended.
Agreement of the measured profiles with the beam model, using water tank data, should be verified annually.
The field width can be influenced by wear in the collimation system. Wiggling of the jaws in longitudinal direction is measured in the TQA module 'Daily QA' using normalized variations in output measured with the exit detector. The rotational jaw variation is expressed in the parameter 'Peak-to-Peak Fluence Variation' (mm). If this parameter is >0.4 mm, jaw position errors may affect the accuracy of treatment procedures (vendors specification).

Output helical

Detector: Monitor Chamber (MC), Ionization Chamber (IC)
Set up: MC: no absorber. IC: cheese phantom, solid water slabs
Interval: MC: daily, IC: weekly

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Tolerance: 3% in homogenous part of dose distribution, 5% otherwise.

Description: It is assumed that all Tomotherapy units are equipped with the Dose Control System (*DCS*). With this system the dose rate is controlled by a feedback loop where output is regulated such that MC reading is constant or within a small window. Strictly speaking the MC reading is not an output reading because a malfunctioning of the MC can give rise to a wrong output while the MC reading is constant. However monitor chamber 2 will interrupt radiation in such a situation. Moreover the absolute readings of the exit detector channels and the ratio 'MC over central detector channel' will also give a strong indication of a problem in the output. In this report we will therefore still assume that MC reading is a measure of the output. Due to DCS, variation in output as function of gantry angle or duration of radiation is minimal.

Consistency of the output should be monitored on a daily basis using the TQA – Basic Dosimetry module which reads and analyses the monitor chamber 1 signal. The system is used in helical mode. This can be done easily in the morning after warm up of the system.

Helical output is monitored weekly using a DQA type of measurement on the cheese phantom with several ionisation chambers. At least one of them needs to be positioned in a homogeneous and high dose region of the planned dose distribution. The measured values can be compared with the values obtained from the Tomotherapy dose planning system.

Output static

Detector: Ionization Chamber (IC)

Set up: Solid water slabs or a (cylindrical) water phantom, e.g. as described in chapter 4 on Dose Calibration, section 6

Interval: weekly when using TomoDirect, otherwise monthly

Tolerance: 3%.

Description: This measurement is a test for output consistency at several (e.g. 4) fixed gantry angles. Every week the measurement is performed at a different gantry angle.

If TomoDirect is available, the measured values can be compared with the values obtained from the Tomotherapy dose planning system. If TomoDirect is not available this measurement cannot be predicted by a dose planning calculation. In order to use such an output measurement (corrected by temperature and pressure and calibration factor) as a reference, it should be cross-correlated with measurements that are linked to a dose calculation (e.g. the TomoPhantom5Sets of equivalent phantom procedure). The measurement can be combined with a PDD measurement with ionisation chambers at two depths.

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3.2.5 Multi leaf collimator properties

Replacement of the MLC

After replacement of an MLC bank, measurements must be performed to obtain: the positioning in lateral direction relative to the source, the position relative to the exit detector, leaf filters (=longitudinal fluence profiles per leaf), latency and LFOF values. The procedure to perform all measurements is available for the Accuray FSE or the first line engineering team. The service application TDAT analyzes the measurements and produces data to update that part of the system that is called the JAM (Jaw Accelerator Machine): LeafTAGLower, -higher, -both, latency data and leaf filter data.

Latency describes the relationship between the effective open times and programmed open times of the Multi-Leaf Collimator (MLC). Leaf fluence output factors describe how Multi-Leaf Collimator leaves affect the signals of adjacent leaves in a variety of positions.

Lateral position of the linac compared to the centre of the MLC is checked by measuring the T&G profile, as described in TQA module ‘Daily QA’. The procedure to calibrate the position of the MLC relative to the detector (‘Fixture Scan’ and ‘Pin Scan’) is described in the T-SVC-00159 physics document. This procedure models leaf profiles (leaf filters) in greater detail and is necessary for a system equipped with a mint drive in order to use TomoDirect.

It is recommended that all ‘reference’ output plans in use in the clinic, be re-optimised and calculated so as to utilise the latest Latency/LFOF/filter parameters.

QA procedure after MLC bank replacement or replacement of isolated leaves

Procedures to measure LFOF and latency are available for the responsible MPE and/or first line support. Analysis of the results and the update of the JAM is checked and approved by Accuray. If the latencies and/or the leaf fluence output factors of the new MLC differ too much from the old values, the MLC is registered as ‘non-equivalent’, disabling all treatment plans of patients currently under treatment. The so-called self-transfer corrects the existing sinograms, taking into account the new MLC properties and avoids re-planning. Note that the self-transfer can only be used if the MLC is effectively registered as non-equivalent.

See chapter 7 on Patient Transfer for more info. If Patient Transfer is not successful, it is recommended to re-plan every patient.

To accept the new MLC, a repeat DQA or a repeat reference treatment performed with a measurement one week or less before the MLC replacement, can be performed. If these results deviate more than 2% from the results acquired with the old MLC, a self-transfer of

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the existing treatment plan procedures could be performed within the Data Management application.

Monitoring MLC properties

Monitoring MLC properties is performed with TQA. These TQA tools can be found in module DailyQA and Stepwedge Helical, as presented in section 3.2.2.

Leakage

Leakage through the closed MLC bank and through the linac shielding should be assessed after MLC, jaw or linac replacement. It allows for detection of manufacturing errors or errors in the placement of shielding material. Leakage can be measured using film. Leakage is approximately 0.3% relative to the open field.

3.2.6 Dynamic behaviour of gantry, couch and MLC

We recommend using the TQA modules ‘Stepwedge helical’ and ‘Stepwedge static’ to measure the behaviour of dynamic parameters couch, MLC and gantry. These modules do not provide information about the synchrony of MLC and gantry.

Note: deviations in dynamic behaviour cannot easily be pinpointed to just one parameter. For example, one cannot tell if the gantry is too fast or the couch too slow.

Gantry rotation – couch translation

Detector: film

Set up: a film with 1.5 cm build up is placed on the couch.

Interval: annually

Tolerance: difference between film maxima within 1 mm

Description: A rotational irradiation is used with the nominal 1.0 cm beam and a pitch of 1 for 13 rotations. The control sinogram is set to open all the leaves for half a rotation on the second, seventh, and 12th rotation. The resulting film is scanned and a profile is produced along the direction of table travel. The resulting profile should show maxima 5 cm apart to within 1 mm.

Note: TQA module Helical Stepwedge can in principle be used to measure gantry – couch synchronicity, making use of gantry phase angle differences measured at the stepwedge level transitions (see paragraph 3.2.2).

Gantry angle – leaf dynamics

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Detector: film

Set up: Two films parallel to the rotation plane and separated on either side of the virtual isocenter by 3 cm

Interval: annually

Tolerance: gantry angles within 1°

Description: A delivery sequence is defined that specifies a slice width of 2.5 cm and a pitch of 0.1 for a minimum of 40 rotations. The control sinogram is set to open the middle two leaves _32 and 33_at projections centred at 0°, 120° and 240°. Using a horizontal line marked on the films during setup, the resulting star pattern can be checked for the correct initial angles at the start of treatment and the ability to reproduce this pattern after 24 rotations.

Gantry angle consistency

Detector: Exit detector

Interval: weekly

Tolerance: gantry period: 0.02%, phase shift: 0.7º

Description: Use TQA module 'Stepwedge helical'. The stepwedge is positioned on the couch according to the green lasers. The parameter 'Gantry phase angle' measures how accurately the measured rotational data is in phase with the reference data. The phase of the stepwedge attenuation centres is compared to a reference set of centres. From this, the phase angle difference, in degrees, is determined. This method supersedes the method recommended in TG148 (see procedure above: Gantry angle – leaf dynamics) only for the gantry angle consistency but not for a measurement of gantry – leaf dynamics.

The 'Gantry period' parameter measures the consistency of the gantry rotation speed by comparing the number of pulses per rotation to reference values. This parameter will only deviate from the reference value given in units of time, whatever the actual gantry speed is, if the tick fence fails (see the item 'Tick fence' in paragraph 3.2.1).

Couch speed uniformity

Detector: Exit detector

Interval: weekly

Tolerance: 0.2%

Description: See the description of the Stepwedge static TQA module in section 3.2.2.

MLC timing of leaf movement

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Detector: Exit detector
Interval: weekly
Tolerance: flash centre: 5 ms, flash width: 5 ms
Description: Measures the timing of leaf movement. See the description of the Stepwedge helical module in section 3.2.1. 'MLC flash centre difference' determines the centre of several exposures caused by short MLC flashes. The results are compared to the reference data to determine if the flash centre has shifted (in ms).
'MLC flash width difference' measures the width of each centre of exposure. It verifies that the leaves are open and closed for the correct amount of time (in ms).

3.2.7 Miscellaneous aspects

Interrupted treatment procedures
Detector: film or detector array
Interval: monthly
Tolerance: 1 mm
Description: Position film or array of detectors (f.i. ArcCheck) on the couch. Start treatment. Interrupt treatment at random position. The couch is automatically retracted to the start position. Do not move the film or array of detectors on the couch. Generate a completion procedure and irradiate this procedure. Analyse the abutment region. Abutment should be within 1 mm. The dosimetric error will then be within 6% (Althof et al., 2012). The local MPE should access the suitability of the array of detectors to perform this measurement accurately.

3.2.8 QA measurement schedule

In TQA the user can design his own measurement schedule. The appendix shows the (T)QA schedule recommended by this NCS subcommittee. The abbreviation SWS stands for Step wedge static and SWH stands for Step wedge helical.
Some QA items are measured in more than one TQA module. As an example: while monthly measurement would suffice for the 'Exit-detector-average-signal to Dose 1', this item is addressed daily because the item is part of TQA module Basic Dosimetry, which is performed daily because of the MC1 output measurement. The column at the most right side in the table shows in which TQA modules a parameter is measured.
Monitor chamber output and cone shape variation are also addressed in several TQA modules, but with different jaw settings. As an example: in module Daily QA the J48 (5 cm slit) is used to measure the cone shape, but the J7 (1 cm slit) jaw variation is more sensitive

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for position variation of the focus point and the J1 (MVCT slice width) jaw detector output variation provides a clearer indication of jaw motion. See the TQA manual for more information on this type of details. From measured QA items, trend parameters are presented by the TQA application automatically. This is useful in accessing the relevance of a deviation in a single measurement to the long term behaviour of a parameter. For instance the trend parameter ‘MC1 standard deviation of the output’, is a measure of output variation consistency. Trend parameters are not described separately in this report. In case no alert levels are known or no alert level is applicable, the alert level is assigned ‘inf’, in line with the TQA manual. Some recommendations are based on the experience of this NCS subcommittee.

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4 Dose Calibration

4.1 Calibration in non-reference conditions

This paragraph is mainly based on the report of the IAEA/AAPM working group on a new formalism for reference dosimetry of small and non-standard fields (Alfonso et al., 2008) in combination with the code of practice for the absorbed dose determination in high energy photon and electron beams (NCS 18, 2008).

The NCS18 formula for the absorbed dose to water at the reference depth in water for a user beam Q in absence of the ionisation chamber is given by formula 4.1.

$$D_w^Q = M_{corr,Q} \cdot N_{D,w,Q_o} \cdot k_{Q,Q_o} \quad (4.1)$$

D_w^Q	The absorbed dose to water at the reference depth in water for a user beam Q in absence of the ionisation chamber under reference geometry (field 10 cm x 10 cm at focus-water-distance of 100 cm).
$M_{corr,Q}$	Reading of the electrometer corrected to ambient reference conditions and for the effects of recombination, polarity and the influence of the electrometer
N_{D,w,Q_o}	The calibration coefficient for the absorbed dose to water for a reference photon beam quality Q_0 traceable to a primary or secondary standard.
k_{Q,Q_o}	Accounts for the effects of the differences between the beam quality Q and the reference beam quality Q_0. If no K_Q is available for the chosen ionization chamber, cross calibration with a chamber with a known K_Q in the NCS-18 reference setting, is needed.

This formulism cannot be used as such for a Tomotherapy machine because the physical limitations of the machine do not permit a broad 10 cm x 10 cm field. The maximum field size allowed is 5 cm (in longitudinal direction) x 40 cm (in the transverse direction). A maximum distance of 28 cm from isocentre (at 85 cm) to the lowest couch position is possible, so the classical reference distance of 100 cm is reachable, but the geometry does not allow a measurement at the reference depth of 10 cm in appropriate backscatter conditions. In addition; the Tomotherapy machine has no flattening filter: the depth dose differs from the depth dose for the same nominal energy on a gantry-based accelerator.

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In the IAEA/AAPM report (Alfonso et al., 2008), a formalism is described for small static field reference dosimetry, specific for machines unable to set-up a conventional reference field. Since the Tomotherapy machine will be most frequently used in helical mode, the use of a static reference field does not seem the best methodology. Nevertheless, also static Tomotherapy fields will be used for patient treatments when using the direct mode. In this view, measurements in a static reference field will be a valuable part of the routine machine QC.

For standardization of composite field reference dosimetry, a plan-class specific reference field is used, recommended to be closer to the patient specific clinical fields. For helical Tomotherapy a composite field means a helical and modulated field. In addition, this calibration procedure for a helical Tomotherapy treatment unit is then integrated in the fluence based planning and delivery methodology. A composite field can be used to link the measured dose for this field to the dose predicted by the planning system.

Note: Tomotherapy dose delivery is controlled by time (more specific: ticks of the gantry rotation) and not by monitor units. Therefore, a monitor unit calibration as in conventional linacs is not appropriate. Of course the monitor chamber plays a crucial role in the interlocking and safety system'.

4.2 Reference dosimetry in a static field: machine specific reference field

The concept of a machine specific reference field (msr) is applicable to machines that cannot establish the conventional reference conditions. Formula 4.2 is applicable for msr dosimetry and is traceable to a 10 cm x 10 cm reference field. For Tomotherapy a 5 cm x 10 cm field is recommended as static msr field (Langen et al., 2010).

$$D_{w,Qmsr}^{fmsr} = M_{Qmsr}^{fmsr} \cdot N_{D,w,Q_o} \cdot k_{Q,Q_o} \cdot k_{Qmsr,Q}^{fmsr,fref} \quad (4.2)$$

$D_{w,Qmsr}^{fmsr}$	The absorbed dose to water at the reference depth in water for a user beam Q_{msr} and reference field f_{msr} in absence of the ionisation chamber
M_{Qmsr}^{fmsr}	The electrometer reading of the dosimeter in f_{msr} corrected for any difference between the ambient air conditions affecting the ionisation chamber at the time of measurement and the standard ambient air conditions for which the calibration coefficient applied (temperature, pressure, ion recombination and polarity effects.
N_{D,w,Q_o}	The calibration coefficient for the absorbed dose to water for a reference photon

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	beam quality Q_0
k_{Q,Q_o}	Accounts for the effects of the differences between the beam quality Q and the reference beam quality Q_0
$k_{Qmsr,Q}^{fmsr,fref}$	Factor to correct for differences in condition of field size, geometry, phantom material and beam quality of the conventional reference field f_{ref} and the machine specific reference field f_{msr}. This factor accounts for differences in response of an ionisation chamber in the fields f_{ref} and f_{msr} and is defined as $$k_{Qmsr,Q}^{fmsr,fref} = \frac{D_{w,Qmsr}^{fmsr} / M_{Qmsr}^{fmsr}}{D_{w,Q}^{fref} / M_{Q}^{fref}} \quad (4.3)$$ More details on this factor can be found in the paper of Alfonso, Thomas and Sterpin (Alfonso et al., 2008; Edmond Sterpin et al., 2012b; Thomas et al., 2005b).

4.3 Practical implementation of reference dosimetry in a static field: defining $k_{Qmsr} = k_{Q,Q_o} \cdot k_{Qmsr,Q}^{fmsr,fref}$ in a Tomotherapy beam

First, one has to focus on beam quality. Because of the absence of a flattening filter the energy spectrum of a Tomotherapy beam will be softer. The following recipe can be used to obtain $k_{Q,Q_o} \cdot k_{Qmsr,Q}^{fmsr,fref}$ (valid in a 10*10cm beam at SSD=100cm) from a PDD measurement in a 5*10cm field at SSD=85cm. Please be aware that a PDD measurement is used to define the beam quality, in contrast with NCS -18 where TPR20,10 is used.

Step 1	Create a 5 cm x 10 cm field using i.e. the basic create function (TomoHD Manual, 2015) on the operation station of the Tomotherapy machine for a well-defined irradiation time. Close the MLC's for the first 10 seconds to allow the beam to stabilize.
Step 2	Define the percentage depth dose (PDD) at 10 cm depth in water for this field, SSD 85 cm and position of the chamber corrected for the effective point of measurement: this is the PDD(10)Q_{msr}. Because this measurement will be performed in an unflattened beam it is important to use a small ionisation

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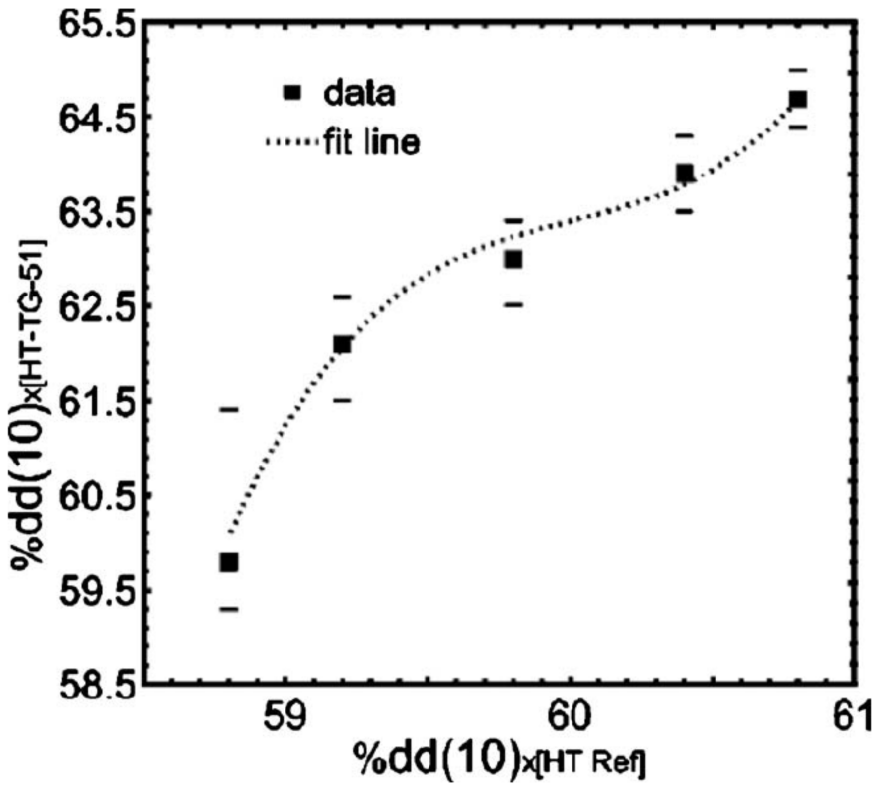
	chamber.
Step 3	Use equation 4.4 to convert the PDD(10)Q_{msr} measured in the f_{msr} to the PDD(10) in the virtual 10cm x 10cm field (f_{ref}) as defined by Thomas (Thomas et al., 2005b) of figure 19 from TG148 (Langen et al., 2010): $\%ddQ = 1.335805.(\%\text{dd(10)Qms r})^3 - 244.493.(\%\text{dd(10)Qms r})^2)$ $+14672.98.(\%\text{dd(10)Qmsr} - 293479.4$ (4.4)  Figure 4.1 (copied figure 19 from TG148): the relationship between Q and Qmsr as measured with an ionisation chamber tabulated in TG51.
	The $\boldsymbol{k_{Qmsr}}$ values listed in table 4.1 are taken from TG51 (Almond et al., 1999) can be used to substitute the composite factor $k_{Q,Q_o} \cdot k_{Qmsr,Q}^{fmsr,fref}$. In the TG51 report k_Q factors are tabulated for different chamber types as function of k_Q for cylindrical ionisation chambers commonly used. The tabulated values can be interpolated linearly in Q.
	Table 4.1 (copied table I from (Langen et al., 2010)). Values of $\boldsymbol{k_{Qmsr}}$ for photon beams as a function of the beam quality, equivalent to the factor $k_{Q,Q_o} \cdot k_{Qmsr,Q}^{fmsr,fref}$.

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	k_{Qmsr}		
	Beam quality specifier $\%dd(10)_x$		
Ion chamber	58	63	66
Capintec PR-05/PR-05P	0.999	0.997	0.995
ExradinAl Shonka[a]	0.999	0.998	0.996
ExradinA12 Farmer	1	0.999	0.996
Exradin A1SL miniature Shonka	0.999	0.998	0.996
PTWN30001 0.6cc Farmer[b]	1	0.996	0.992
PTW N30002 0.6cc all Graphite	1	0.997	0.994
PTW N30004 0.6cc Graphite	1	0.998	0.995
PTW 31003 0.3cc waterproof[c]	1	0.996	0.992
WellhoferIC-10/IC-5	1	0.99	0.996

[a]The cavity radius of the A1 here is 2 mm although in the past Exradin has designated chambers with another radius as A1.
[b]PTW N30001 is equivalent to the PTW N23333 it replaced.
[c]PTW N31003 is equivalent to the PTW N233641 it replaced.

PDD(10)$_x$ for cylindrical ionisation chambers commonly used for clinical reference dosimetry. The tabulated values can be interpolated linearly in PDD(10)$_x$

This table includes the value k_{Qmsr} (originally in this table denoted as: k_Q) as calculated by Thomas (Thomas et al., 2005b) for the Exradin A1SL ionisation chamber. The value k_{Qmsr} for a static 5 cm x 10 cm Tomotherapy beam equals between 0.995 and 0.999 for most common cylindrical ionisation chambers. For other chambers references can be found (Sterpin et al., 2012; Zeverino et al., 2011).

Remark 1 : when using a solid water phantom from the material provided by Accuray one needs to be aware that at the isocentre, at 10 cm depth, the use of this solid water accounts for a factor $D_{w,solid\ water}/ D_{w,water}$ =0.995 ± 0.003 (1SD) as calculated with MC calculations (De Ost et al., 2011).

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4.4 Practical implementation of reference dosimetry in a static field: defining $D_{w,Qmsr}^{fmsr}$

Step 1	Create a 5 x 10 cm field using for example the basic create function (TomoHD Manual, 2015) on the operation station of the Tomotherapy machine for a well-defined irradiation time. Close the MLC's for the first 10 seconds to allow the beam to stabilize.
Step 2	Set up the water phantom and position the ionisation chamber at a distance of 85 cm SSD on a depth of 10 cm water. Allow the chamber to equilibrate at the water temperature.
Step 3	Take ionisation readings per time unit at positive and negative polarization voltage of the chamber to define the polarity correction kpol. Take ionisation readings per time unit at high (U2) and low voltage (U1) of the chamber to define the recombination correction ks as described in NCS report 18- appendix 2 (NCS 18, 2008). Valuable information on this topic can also be found in Palmans (Palmans et al., 2010) where the need for a correct determination of the recombination correction is expressed, especially for the ion chambers smaller than the Farmer type chambers. .
Step 4	Record pressure and temperature and correct your reading: $P_{TP} = \frac{273.15+T}{273.15+T_0} \times \frac{P_0}{P}$ (4.5)
Step 5	Calculate the corrected ionisation chamber reading: $M_{Qmsr}^{fmsr} = M_{raw} \cdot k_s \cdot k_{TP} \cdot k_{elec} \cdot k_{pol}$ (4.6)
Step 6	Calculate the dose to water per time unit at the depth of measurement: $D_{w,Qmsr}^{fmsr} = M_{Qmsr}^{fmsr} \cdot N_{D,w,Q_o} \cdot k_{Q,Q_o} \cdot k_{Qmsr,Q}^{fmsr,fref}$ (4.7)

4.5 Reference dosimetry for a composite field: Plan-class specific reference field

Secondly the concept of a plan-class specific reference field is used to standardize composite field dosimetry. The plan-class specific reference (pcsr) field is a reference field for a class of combinations of fields in a configuration representing the clinically delivered treatment. The pcsr field must deliver a homogeneous dose to an extended and simple geometrical target volume.

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For Tomotherapy the treatment machine cannot establish a conventional reference field and the dosimetry of the plan-class specific reference field is referred to a machine specific reference field. An extra conversion correction is needed between the msr and the pcsr fields:

$$D_{w,Qpcsr}^{fpcsr} = M_{Qpcsr}^{fpcsr} \cdot N_{D,w,Q_o} \cdot k_{Q,Q_o} \cdot k_{Qmsr,Q}^{fmsr,fref} \cdot k_{Qpcsr,Qmsr}^{fpcsr,fmsr} \qquad (4.8)$$

$k_{Qpcsr,Qmsr}^{fpcsr,fmsr}$	Factor to correct for the differences between the conditions of field size, geometry, phantom shape/material and beam quality between fmsr and fpcsr This value is equal to 1.003 for most commonly used ionisation chambers (NCS 18, 2008).

4.6 Practical implementation of reference dosimetry for a composite field: defining $D_{w,Qpcsr}^{fpcsr}$

Step 1	Take a CT scan of a water equivalent phantom with dimensions large enough in relation to the volume (see step 2) you will treat. The phantom should be scanned without the ionisation chamber present.
Step 2	Create a cylindrical target volume in this phantom around and exceeding the active ionisation chamber volume. In TG148 a target volume of diameter 8 cm and 10 cm in length is recommended, together with a 5 cm treatment slit width and a pitch of 0.287 (Palmans et al., 2010).
Step 3	Make a dose plan to generate a uniform dose distribution to this target volume and define the dose to the active volume of the ionisation chamber.
Step 4	Place the phantom with the appropriate ionisation chamber on the treatment couch; MVCT-scan the phantom to check the setup. Deliver the plan on the machine.
Step 5	Ionization measurements must be collected for the prepared plan. And dose must calculated with $D_{w,Qpcsr}^{fpcsr} = M_{Qpcsr}^{fpcsr} \cdot N_{D,w,Q_o} \cdot k_{Q,Q_o} \cdot k_{Qmsr,Q}^{fmsr,fref} \cdot k_{Qpcsr,Qmsr}^{fpcsr,fmsr}$ (4.9) With $k_{Q,Q_o} \cdot k_{Qmsr,Q}^{fmsr,fref}$ (static 5 cm x 10 cm field) determined using the recipe described in section 4.3 $k_{Qpcsr,Qmsr}^{fpcsr,fmsr}$ =1.003 for Tomotherapy 5x10cm (Langen et al., 2010).

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Step 6	Compare calculated and measured output.
Step 7	If a systematic deviation is found in the machine specific reference field and the plan class reference field, the Accuray field service engineer or a trained in house engineer must adjust the output and the output measurements must be repeated. Maybe a DCS calibration is necessary afterwards.

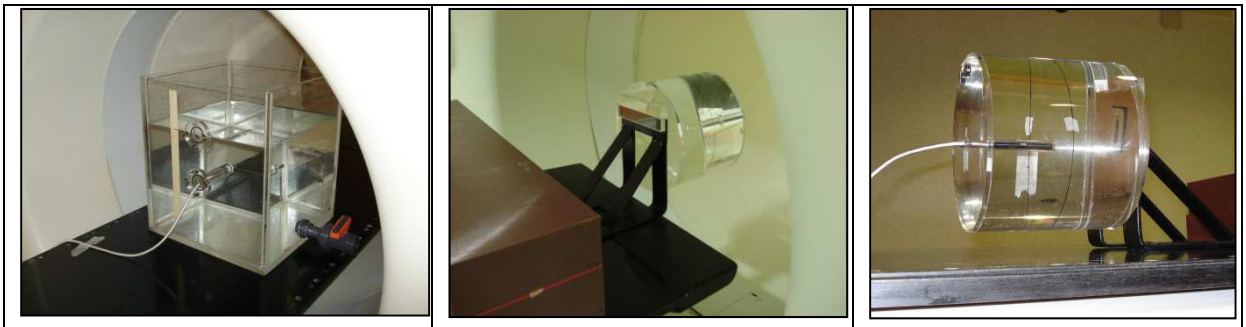

Figure 4.2 Water phantoms as used for the measurement of the beam output for a static MSR field (left) and for rotational deliveries (middle). The perspex water filled cylindrical phantom allows a couch top-free positioning into the bore of the Tomotherapy system. Right: the cylindrical water phantom positioned on the couch for the plan specific reference field measurements.

Dosimetric validation test

The standard cylindrical solid water phantom (the so-called cheese phantom) is useful for dosimetric validation. In this phantom A1SL chambers (or any other calibrated chamber that fits) can be placed on various locations in a horizontal or vertical plane. Plans designed to treat on-axis and off-axis cylindrical targets should be generated for each clinically used slit width, using a normal dose grid. The targets must have a significantly larger volume than the sensitive volume of the ionisation chamber. Multiple point dose measurements must be performed in high and low dose regions. Plans should be generated for both helical and direct treatment mode. There is no fundamental difference between the plans generated for dosimetric validation and the pcsr field. Some validation procedures are also generated by Accuray (TomoPhant or TomoDirectPhant). By using these latter plans and corresponding phantoms, we do not use the local IVDT (image value to density table) but the one generated by Accuray. The acceptability criteria for IMRT plans recommended by the NCS (NCS 22, 2013) are 3%/3mm.

Audits are a valuable factor in dosimetric validation of a system. It is recommended to participate in local, national or international audits before the treatment unit is used for patient treatments and on regular basis once the system is in clinical use (Alvarez et al., 2016; De Ost et al., 2011; Duane et al., 2006).

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4.7 Recommendations on tolerance limits and Interval

Table 4.2 Recommendations		
Daily	Consistency of rotational output using exit detector	2%
Weekly	Consistency with TPS rotational Output pcsr	3%
Monthly	Consistency static output with IC	2%
Annually	Reference dosimetry pcsr field	1%

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5 MegaVolt CT imaging system

5.1.1 Overview

The MVCT imaging system of the Tomotherapy system uses the linac, which is used for the treatment of the patients, as the source of radiation. For the MVCT image acquisition, the linac runs with a pulse rate of 80 Hz and is slightly detuned. This results in a reduced energy of about 3.5 MeV and a lowered dose rate, depending on the selected pitch (Jeraj et al., 2004). The linac is controlled by the *DCS* system and furthermore the CT-detector signal is normalized with the signal of the monitor chambers to ensure a constant baseline signal during the scan.

The CT detector is located on the opposing side of the ring gantry at a distance of approximately 145 cm, depending on the type of the detector. There are four different types of CT-detectors in the field, all containing xenon filled ionisation chambers, and with 520 to 540 detector channels being in the imaging beam (Chao, 2015). Except for the latest generation of the CT-detectors, which is manufactured by Accuray itself, the radius of the detector is not consistent with the distance from the target, resulting in a defocusing of the detector. This effect results in a typical dip in the central part of the profile, which is accounted for by the normalization of the measured signal with an airscan (section 3.2.2). During an airscan procedure the imaging beam is measured on the detector without any material in the beam. It is recommended to acquire the airscan on a daily basis.

For the MVCT scan the beam is collimated by the jaws to an effective slice width of ~4mm (FWHM) at the isocentre (Accuray 2010). The lateral limitation of the beam results in a Field of View (FOV) of 40cm.

The image reconstruction algorithm needs 180° of rotation for the reconstruction of one image. Thus, two image slices are generated per full rotation of typically 10 sec. The user can choose to double the number of reconstructed slices per rotation. The slice width will be divided by two, accordingly. The slice width is dependent on the pitch of the selected scan procedure, for example a pitch of 1 results in a couch movement of 4mm during one rotation and therefore one image has a slice thickness of 2mm. Predefined pitches of 1, 2 and 3 are available and can be selected as fine, normal and coarse under the imaging tab at the operator station. Additionally, for each slice thickness the slice separation can be selected to be either the same as the slice thickness, or to be half of it. A smaller slice separation results in a better resolution in the sagittal and coronal images reconstructed from the axial slices. However, for the use of the images in the registration process, the displayed axial MVCT images are interpolated to fit the images from the planning CT scan. A filtered back

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projection algorithm with a 512x512 matrix is used for the reconstruction of the images, resulting in images of the same dimension (Accuray, 2013a).
Due to the higher energy of the MVCT compared to a conventional CT scanner, the soft tissue contrast is reduced but still useful for the process of image registration. If materials with a high Z-value are present in the scan region, the resulting artefacts are small compared with those obtained with a kV imaging beam.

5.1.2 Use of MVCT images

The main use of the MVCT images is the registration process with the planning CT, where the patient is set up in the correct position. Furthermore, the anatomy of the patient at the time of treatment is checked.
If a change in patient anatomy is observed, the MVCT scan can be used to recalculate dose and adapt the following treatments to the new situation. This process is facilitated by the Tomotherapy Planned Adaptive application (see chapter 7).
When materials with a high Z-value are close to the target volume it might be favourable to perform the treatment planning on basis of an MVCT scan, because of the reduced artefacts. In this case the MVCT images can be exported to a third party product for contouring and then be reimported on the Tomotherapy system for the planning process.

5.1.3 Standard Workflow

During the treatment planning process, the positions of the red lasers are set to the markers visible on the planning CT scan. When the patient treatment plan is selected, either manually or via a record-and-verify system, the scan tab is opened and the scan region, the acquisition pitch and the reconstruction interval are chosen. Once the procedure is approved, the gantry starts to rotate and the red lasers move to the positions specified in the treatment plan. In the treatment room the patient is immobilized on the treatment couch and positioned in accordance with the red lasers.
After the scan is completed the registration parameters are selected under the Register tab. Normally, the process starts with an automatic registration, where the following parameters need to be selected. First, a density threshold value, which identifies the voxels used for the registration process, is selected. The options are bone (density > 1.1 g/cm^3), bone&tissue (density > 0.3 g/cm^3) and full image (no threshold). The next selection deals with the resolution of the images during the registration process. The options are superfine (no down sampling), fine (down sampled by a factor of 2 in left-right and anterior-posterior direction) and standard (down sampled by a factor of 4 in left-right and anterior-posterior direction)

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(Accuray, 2013b). Furthermore, the user can chose which degrees of freedom (3 translations and 3 rotations) are considered for the registration. The most frequently used option is to use all translations plus the roll correction (IEC-Y axis), since these corrections can be easily applied by means of a couch translation and gantry rotation. Finally an option to consider the case that the patient is not completely covered by 40cm FOV, called 'incomplete Field of View' can be selected.

Once the automatic registration is done, manual corrections are possible. There is no option to limit the region for the automatic registration. Therefore, fine adjustments might be needed since, in general, the focus of the registration should be on the region of the target volume and critical organs at risk.

When the registration is approved and applied to the treatment procedure, the red lasers are performing the same movement as the couch with the patient. Therefore the red lasers should again be located on the markers of the initial setup, enabling the operator to check whether the patient has been moved correctly. Once the new position is approved (this can also be done from the control room without checking the lasers), the treatment of the patient can start.

5.1.4 HU CT number calibration and IVDT check

See chapter 7.1.5 'QA on Planned Adaptive', were the MVCT is used for dose calculation.

5.2 Geometry

The further use of MVCT patient images, acquired either for the setup of the patient and/or for adaptive recalculations, depends on a correct geometry in the images. This applies to correct dimensions, correct orientation and correct localization of an imaged object.

For the description of the tests it is assumed that the virtual isocentre is linked to the machine isocentre. If the internal procedure is such that the couch height is compensated for the couch sag caused by the patient weight, the associated weight should be placed on the couch top, or a correction in the vertical direction needs to be applied for the evaluation of the image location with respect to the isocentre. Alternatively, the couch height can be set in the bore at the machine isocentre using the green laser which projects a cross through the isocentre from the backend of the bore.

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5.2.1 Orientation

Procedure: A phantom with a characteristic shape to clearly identify the left or right side (IEC X), the top or bottom (IEC Z) and start or end (IEC Y) of the phantom is scanned. In the Registration tab of the Operator station and the planned adaptive software, but also in the Dose Planning and in the Patient Transfer application, the correct orientation in the image stack is checked. For the IEC Y direction a sagittal or coronal reconstruction can be used.

Parameter and tolerance: The correct orientation of the images should be recorded for every IEC direction.

Interval: Annually or after a software update

Comment: When a phantom has a symmetry, which makes it difficult to identify the correct orientation, additional markers or objects can be placed in the scanned region of the phantom.

5.2.2 Scaling, rotation, distortion

Procedure: A phantom with well-defined points at well-known distances is scanned with a slice thickness of 2mm (fine, 1mm slice separation). The selected scan range should be long enough compared to the inherent inaccuracy due to the slice thickness. At the operator station the measuring tool in the registration tab can be used to measure the distances of the markers in the scanned image. The markers should cover the image in order to be sensitive for distortions in the image. At least two of the markers should be in a horizontal, or a vertical, configuration. This configuration is checked in the registration tab by the use of the displayed lasers, or the slice indicators. For a well-defined point of the couch, it is checked that the location of the point in the image does not move when scrolling through the acquired images. This way it is checked that the image stack is not rotated around the two axis located in the image plane. A minimal rotation of the image stack around the IEC X axis might occur due to the couch sag.

Parameter and tolerance: A set of distances, covering at least every cardinal direction is recorded. The results should be within 1mm.

By the use of additional markers, or additional details in the phantom, it should be recorded that the image is free of distortions.

The fact that the image stack is not rotated needs to be recorded. Depending on the used phantom and markers, displacement of these markers can be defined, corresponding to certain rotations.

Interval: Annually or after a software update.

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Comments: If surfaces and interfaces of phantoms are used instead of markers, the measurements should be performed with well-defined values for level and window in the image.
When symmetric positions are measured with respect to the isocentre, this test can be combined with the test for the location of the images relative to the isocentre.

5.2.3 Location virtual isocentre to machine isocentre

Procedure: A marker is placed at the virtual isocentre using the green laser system and a scan with sufficient scan length around the isocentre is performed. The deviation of the marker from the isocentre, displayed in the image by green lines (available in the registration tab on the operator station) is measured.
Parameter and tolerance: The deviations in the three cardinal directions are recorded. The results should be within 1mm.
Interval: monthly.
Comment: Alternatively a larger phantom can be used, if positioned symmetrically to the isocentre. In this case the distances from the displayed isocentre to the edges of the phantom must be identical.

5.2.4 Overlap red and green lasers

Procedure: In their ‘zero’ position the red lasers should overlap the green lasers. This is checked visually.
Parameter and tolerance: The deviations in the three cardinal directions are recorded. The results should be within 1mm.
Interval: weekly.

5.3 Image Quality

The image quality of the MVCT scans needs to be sufficient for the intended use, such as the registration with the treatment planning CT scan for patient setup, adaptive recalculations, or contouring for StatRT. The reference values for the image quality are usually determined during the ATP of the system.
There are two classes of artefacts, which can be present in the MVCT images. The first class contains the so called ‘button artefact’ and the ‘zipper artefact’. For both artefacts correction algorithms are implemented in the Tomotherapy software. The correction only applies to the display of the images on the operator station, while the images stored in the database are

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not corrected. The second class of artefacts is the ‘ring artefact’ and the ‘streak artefact’, which are due to defective parts in the machine and are also well known in CT technology. On occurrence, corrective measures on the machine will be undertaken.

5.3.1 Noise

Procedure: A MVCT scan of a homogeneous, water equivalent phantom with a minimum diameter of 20 cm is acquired. In the slices a large enough ROI (approx.100cm^2) is contoured and the standard deviation of the HU values is determined. This will serve as a measure of noise in the image (Meeks et al., 2005).

Parameter and tolerance: The standard deviation of the selected ROI is recorded. The value should be in the order of 35 HU, the reference noise level should be determined during or immediately after the ATP process by the MPE.

Interval: Monthly.

Comment: Since the ‘Tomotherapy-Software’ does not have a tool for a statistical evaluation of HU values of a ROI, a transfer to a third party software is necessary (e.g. ImageJ).

The ROI should be located in a region of the phantom which is free of artefacts and density fluctuations. Specifically the centre of the images should be avoided because of the button artefact.

5.3.2 Uniformity

Procedure: A MVCT scan of a homogeneous, water-equivalent phantom with a minimum diameter of 20 cm is acquired. 5 small ROIs (diameter of approx. 1cm and a length of approx. 10 slices) are contoured, one in the centre and the other four are located in the cardinal directions close to the border of the phantom. The mean value of the HU for each of the 5 ROIs is determined.

Parameter and tolerance: The maximum value of the deviation of the peripheral ROIs from the central ROI is recorded. The value should be less than 25 HU, limiting errors in dose computation to < 2.5%.

Interval: Monthly.

Comment: Since the ‘Tomotherapy-Software’ does not have a tool for a statistical evaluation of HU values of a ROI, a transfer to a third party software is necessary (e.g. ImageJ).

The ROIs should be located in a region of the phantom that is free of artefacts and density fluctuations. Specifically, the exact centre of the images should be avoided because of the button artefact.

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5.3.3 Resolution

Procedure: A MVCT scan of a phantom containing a high contrast resolution pattern is acquired. The representation of the high contrast resolution pattern in the images is evaluated. The user decides up to which resolution the pattern is visible.

Parameter and tolerance: The size of the detectable object or an equivalent indicator (e.g. lines or rows) is recorded. The vendor specifies an object size of 1.6 mm, which should be detectable (Accuray, 2013c). The reference should be determined during the ATP.

Interval: Monthly.

Comment: Usually the high contrast resolution plug, which comes with the cheese phantom, is used for this purpose. The resolution specified by the vendor corresponds with the third row of the holes (from large to small).

The evaluation of this test is observer dependent. The values for window and level, used for the reference, and the reference images should be available to the observer.

5.3.4 Contrast

Procedure: A MVCT scan of a phantom with a density of approximately 1 g per cm^3 containing homogeneous regions with densities slightly different from 1 g per cm^3 is acquired. The increments in density should enable the observer to judge which differences in density are detectable in the images.

Parameter and tolerance: The density of the plugs (above and below 1 g per cm^3), which can be detected in the images, is recorded. The reference should be determined during the ATP.

Interval: Monthly and after every software change and after every work on the beam line or the detector.

Comment: Usually the cheese phantom with the included density plugs is used for this purpose.

The evaluation of this test is observer dependent. The values for window and level, used for the reference, and the reference images should be available to the observer.

5.3.5 Artefacts

Procedure: A MVCT scan of a homogeneous phantom with a sufficient diameter is acquired. The images are inspected for the ring- and streak-artefact. The appearance of the button- and zipper-artefact is analysed qualitatively.

Parameter and tolerance: The images are evaluated for the presence of ring or streak artefacts. The magnitude of the button and zipper artefact is compared with the reference

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images from the ATP. It is recorded that the artefacts have not become more prominent than during ATP.

Interval: Monthly and after every software change and after every work on the beam line or the detector.

Comment: The artefact correction should be turned off for this test, since the tests should be able to detect a change in the performance of the imaging system.

For the button and zipper artefact the values for window and level, used for the reference, and the reference images should be available to the observer. For the ring and streak artefact images with examples should be available to the observer to help identifying the artefacts.

5.4 Dose MVCT scan

Although the dose delivered to the patient by the MVCT scan is small compared to the therapeutic dose given during treatment, it is important to ensure that the dose is not higher than reasonably achievable. Doses of less than 3 cGy (typically 1.5 cGy) are specified by the vendor in the centre of the cheese phantom for a scan length of 10 cm.

5.4.1 Dose per scan

Procedure: A phantom containing a calibrated ionisation chamber is placed on the couch and a scan of the region +/- 5 cm from the ionisation chamber is made. This is considered a typical clinical relevant scan length. Accuray specifies a minimum of 7 slices centred around the chamber. The measurement should be performed for the smallest pitch used in clinical routine (scan setting ‘fine’). The setting of the measurement, such as used phantom, ionisation chamber and position of the ionisation chamber and the phantom, should be the same as during the measurement of the reference values.

Parameter and tolerance: The dose measured by the ionisation chamber is recorded. The dose should be less than 3 cGy.

Interval: Monthly.

Comment: The measurement can easily be integrated in the setup process of the individual plan verification measurement.

For the exact measurement of the dose delivered by the imaging beam, correction factors for this beam quality would be needed. However, since the dose delivered by the MVCT is about a factor 100 smaller than the prescribed dose per fraction, the percentage deviations in beam energy correction factors are of limited interest. The absolute values of the deviations should

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be recorded. Typical doses delivered to the patient by a MVCT scan are in the range of 1-2 cGy (Shah et al., 2008).

5.5 Patient Setup

5.5.1 Registration and positioning

The main use of the MVCT is for the correct setup of the patient before the treatment. For this purpose the acquired MVCT scan is registered with the treatment planning CT scan and translational and rotational correction parameters are determined. The translational shifts are applied to the patient by couch movements, supported by the system, while the Roll-correction (around IEC-Y axis) is applied by a phase shift of the gantry rotation. The other two rotations cannot be corrected by the system and can therefore be excluded from the registration process.

The moveable 'red laser' system provides an option to double check the repositioning of the patient. Accurate repositioning of couch and red lasers is essential for a successful treatment of the patient.

Procedure: A MVCT scan of a phantom containing multiple well-defined points inside the phantom is acquired. The points should have external markers on the phantom, which are easily detectable in the MVCT scan. If a dedicated phantom with detectable markers inside the phantom is used, the external markers are only needed for the laser and therefore don't need to be detectable in the MVCT scan. The coordinates of the points need to be well known. Reference values can be obtained by the use of the planning kVCT scanner.

The phantom is positioned on the couch with one of the points (start point) located in the isocentre by using the green laser. The scan region needs to cover one of the other points (target point), which will then be registered to the isocentre. Once the scan is completed, the Registration tab is selected and the display of the lasers is turned on. By using the manual registration option the target point is moved to the isocentre position. If the target point is not detectable itself, this is done with help of the external markers. When this is done, the registration is applied and a treatment procedure is loaded. On the PCP, or the corresponding window at operator station, 'setup' is selected to move the phantom in the registered position. In the treatment room the user verifies that the target point has moved to the isocentre (green lasers) and that the start point is marked by the red lasers.

Parameter and tolerance: The shifts, which are determined during registration, are compared with the reference distances between the points. Additionally, the correct movement of the red lasers (to the starting point) and the end-position of the target point (isocentre = green lasers) is recorded. All deviations should be less than 1 mm.

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Interval: Weekly.

Comment: If only two points are used, the start and target point should be alternated.

The MVCT slices are reconstructed for the positions of the slices of the reference planning CT data set. If markers are not located in a reconstructed slice and therefore difficult to register, it is possible to move the complete data set in IEC-Y direction. Once the correct IEC-X and IEC-Z position are found the correct IEC-Y position must be adjusted.

5.5.2 Red laser reference point set up

The red laser system is used to set up the patient before the start of the MVCT scan. The range of movement in this step is larger than at registration. The coordinates for the lasers are obtained during the planning process, where the lasers are set according to markers on the patient. Although the final setup of the patient is normally determined by the use of the MVCT scan, the red lasers are of particular interest, when patient positioning is performed without a MVCT scan.

Procedure: A treatment procedure or a MVCT scan for Patient (or a calibration procedure) with well-defined laser positions is loaded on the operator station. In the treatment room the laser positions relative to the virtual isocentre (green lasers) are measured.

Parameter and tolerance: The measured positions are compared with the values stored in the procedure. The deviation should be less than 1mm.

Interval: Monthly.

Comment: The full range of the lasers (+/- 18 cm) should be tested.

5.5.3 Rotational setup correction

During the registration process not only translational shifts can be detected. It is also possible to detect rotational setup errors. While the rotations around the IEC-X and IEC-Z axis are difficult to account for, it is quite simple to correct for rotations around the IEC-Y axis (roll). This can be performed by a simple offset to the gantry angle of the treatment procedure. This offset angle can be set manually or automatically during the registration process.

Procedure: A number of methods can be used to measure the applied roll correction. 1) A procedure with a static beam under a well-defined angle is generated. This procedure is applied to a phantom that is able to detect the gantry angle. In a next step, the phantom is exposed by the same procedure, but this time a representative roll correction is applied in the registration tab. The angle between the two beam lines is measured and compared to the applied correction angle. 2) If available, the ‘TQA Helical Stepwedge’ procedure can be used

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to detect a shift in the gantry phase by applying a roll correction in the registration tab. See chapter 3.2.2 TQA module description. 3) A film located in the treatment plane can be used as a phantom. Angles can be measured mechanically, or by using software tools.

Parameter and tolerance: The measured angle between the two beam lines is recorded and compared to the one set under the registration tab. Tolerance is 1º.

Interval: Monthly.

Comment:

The used angles should be in the order of clinically relevant corrections and should be both positive and negative.

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6 Quality assurance of treatment planning system

The particularity of the Tomotherapy delivery system makes most of the traditional commissioning tasks for quality assurance of TPS not applicable. To understand the particular issues for Tomotherapy treatment planning quality assurance, adequate knowledge of the various steps involved in the dose delivery computation and treatment preparation processes is required. Several TPSs have now the capability to generate Tomotherapy treatment plans: the original Tomotherapy treatment planning system, Precision from Accuray and RayStation from RaySearch. The treatment planning system under consideration here is the one that has been historically and, until recently, exclusively delivered with the Tomotherapy system. Experience must be gained for the other systems before making recommendations.

The first task of this chapter is providing a global overview of the TPS before moving to more practical considerations regarding quality assurance. Some TPS features vary from one version to another. To make the argument precise, information on the version number is given for features not available for all versions. Only versions above number 2 are accounted for in the present document since former versions are no longer installed on existing units.

6.1 Introduction to Tomotherapy treatment planning

All Tomotherapy systems follow the same treatment planning workflow for all individual patient/phantom cases through successive panels selected by the user. Before moving to a given panel, all tasks from the previous panels must be properly completed by the user. The various steps involved can be summarized as follows:

1. Image import, replacement of CT imaging couch by Accuray treatment couch.
2. Definition and/or correction of imported target volumes and organs-at-risk.
3. Definition of global treatment planning parameters (patient isocentre (version 4 of Hi-Art systems, version 1.x and higher for TomoHD)), red lasers positioning, TomoHelical or TomoDirect (version 4 of Hi-Art, version 1 and higher for TomoHD systems), patient Image Value-to-Density Tables (IVDT) selection, pitch, field size, modulation factor.
4. Optimization
5. End of planning (EOP) and fractionation (machine treatment plan generation).

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The second point is beyond the scope of the present report. Red laser positioning is linked to imaging (chapter 5). Quality assurance for IVDT curve will be detailed in chapter 7. The objective of the following subsections is to provide the necessary information for a thorough understanding of the optimization and end of planning processes.

6.1.1 Static beam model

Tomotherapy systems share three gold standard beam models (GS), depending on the brand of the linac and the date of the release of the machine. The original one is for the Siemens linac (‘legacy’ model). The second for the first TwinPeak linac (the ‘TP’ model) and the third for the TwinPeak+1 linac (‘TP+1’ model). TP and TP+1 models can be extended to dynamic jaws. Static dose distributions for all three models are very close to each other, as shown in Figure 6.1.

For a given configuration of the system, the manufacturer tolerances for reproducing the corresponding GS are: ratio measured/modelled within 0.98-1.02 for 10mm-200mm depths for percent depth-dose. Longitudinal profiles symmetric: ±1% of reference FWHM, and gamma 2% in vertical / 1% FWHM in horizontal (0.1 mm for 1 cm slit). Longitudinal asymmetric: no tolerance on FWHM and gamma 2%/0.5 mm. Lateral (cone) profile: ±1% of reference FWQM and gamma 2%/1mm. However, some model parameters are unit-dependent. These include leaf fluence output factors (LFOF) and leaf filters, leaf latencies and jaw fluence output factors (JFOF). Leaf-fluence output factors account for the fact that the output for a single open leaf is not the same as the output for the same leaf but with the adjacent leaves opened. Leaf latencies are approximate measurements of the effect on output of the non-instantaneity of leaf opening/closing (Westerly et al., 2009). Since for all current treatment modalities the treatment couch is moving in the longitudinal direction, the dose is directly proportional to the energy-fluence integrated over the longitudinal direction. Jaw fluence output factors account for fluence reduction due to both field size reduction and partial screening of the source by the jaws (Hundertmark et al., 2011). Partial screening is significant for the 1 cm field (output reduction in the order of 10% (Sterpin et al., 2010)). The 2.5 and 1cm jaw fluence output factors are defined with respect to the 5 cm nominal field output, the latter being shared by all Tomotherapy machines. Deviations from the TPS in output for standard helical deliveries generated by 1 or 2.5 cm fields compared to the one generated by the 5 cm field may need correction to some extent. Fine-tuning of the jaw positions may be performed by applying an offset to the encoder count driving the position of the jaws for every commissioned field size. An additional global output correction may need to be performed until measured and computed dose distributions match for standard helical

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deliveries generated with all commissioned field sizes. However, the measured longitudinal profiles must still match the GS within the aforementioned tolerances. The methodology described in this last paragraph aims to correct small inconsistencies of a few percent in dose output with jaw size.

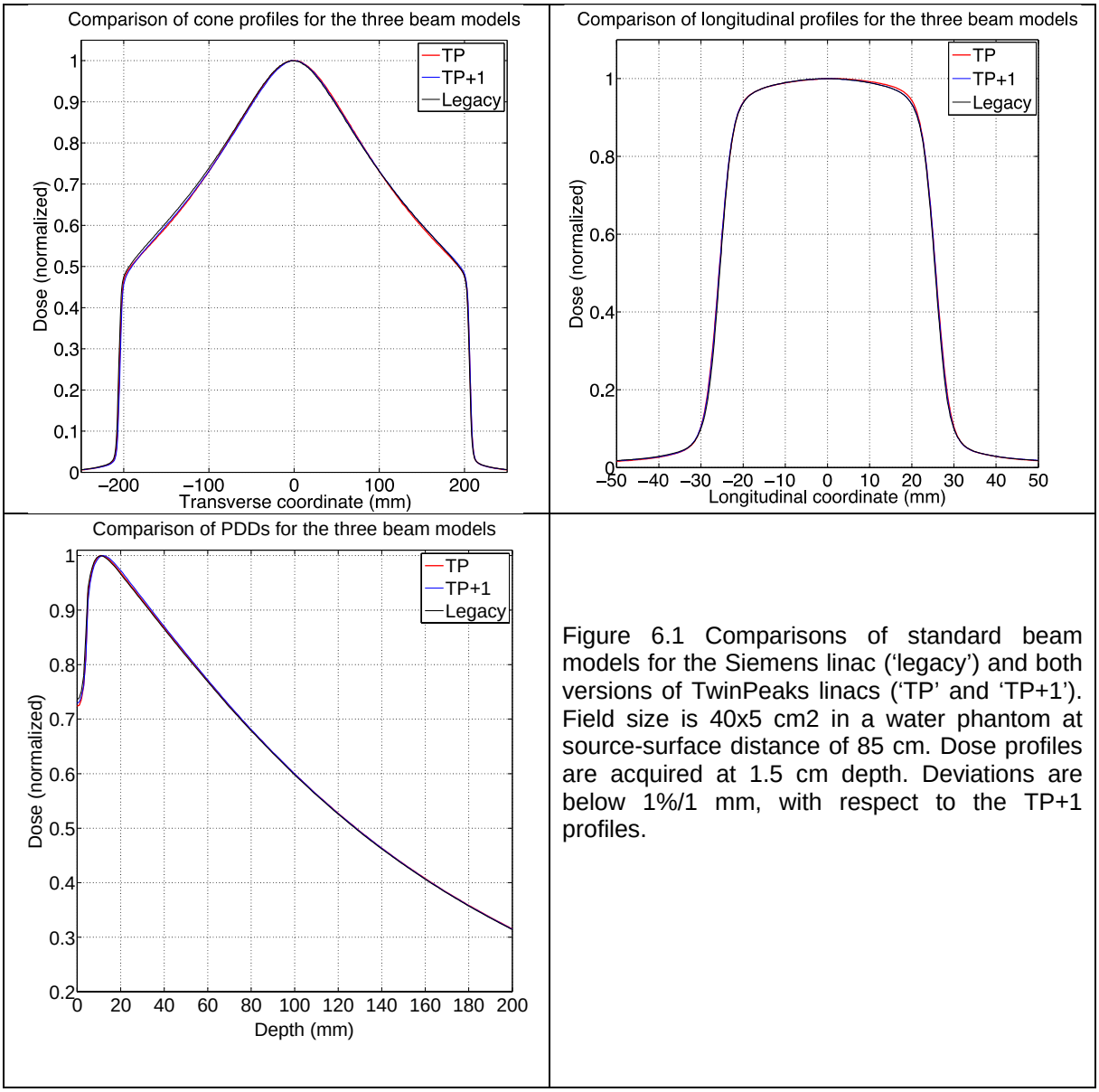

Figure 6.1 Comparisons of standard beam models for the Siemens linac ('legacy') and both versions of TwinPeaks linacs ('TP' and 'TP+1'). Field size is 40x5 cm2 in a water phantom at source-surface distance of 85 cm. Dose profiles are acquired at 1.5 cm depth. Deviations are below 1%/1 mm, with respect to the TP+1 profiles.

6.1.2 Dynamic jaws (TomoEdge)

TomoEdge requires specific modelling of the jaws that are of asymmetric widths at the superior and inferior edges of the target volumes. Treatment plans for multiple targets can take advantage of this improved dose gradient if these are separated by at least one field width in the longitudinal direction.

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A beam model is built based on fits to (standardized) measurements of several dose profiles acquired for several jaw positions. Examples of such profiles are shown in Sterpin et al. (Sterpin et al., 2011). The model can then be used for all jaw positions by interpolation and shifting of the fitting functions.

It is worth pointing out that the TPS does not optimize jaw motion based on clinical constraints. The trajectory of the jaws is determined before optimization and is based on the contours of the PTV volume as described in Chen (Y. Chen et al., 2011).

6.1.3 Dose computation algorithm

The dose calculation algorithm of the Tomotherapy TPS is a collapsed-cone convolution/superposition (C/S) model. The principles of the algorithm may be found in Ahnesjo (Ahnesjö and Aspradakis, 1999). For CPU-based Tomotherapy TPS, more specific information on the Tomotherapy C/S algorithm may be found in Lu (Lu et al., 2005) and manufacturer manuals. For the TPS running VoLO (GPU-based), an abundant literature on the physics underlying the C/S algorithm may be found elsewhere ((Chen et al., 2012; Q. Chen et al., 2011; Lu, 2010; Lu and Chen, 2010)). The performance of Tomotherapy C/S in patient inhomogeneities was evaluated in several studies (Ardu et al., 2011; Sterpin, 2015; Sterpin et al., 2009; Zhao et al., 2008) and was found to be at the level one can expect for a collapsed-cone based algorithm. The equivalence in terms of accuracy between cluster-based and GPU-based dose calculation algorithms has been studied in Chen et al. To make the GPU-based dose engine efficient, changes to the C/S algorithm have been performed. The impact of these changes on dose calculation accuracy was studied using MC simulations by Chen et al. (Chen et al., 2012) and demonstrated negligible for homogenous/heterogeneous phantoms and a large set of patient cases.

For all optimization modalities and EOP dose calculation, the user may select three different dose calculation grids in the transverse plane, coarse, normal and fine. The y-axis remains at the resolution of the planning data set. In the fine resolution mode, the dose calculation grid is the same as the kVCT image. In normal resolution, dose is computed over 4 voxels of the imported kVCT image and in coarse resolution, the dose is computed over 16 voxels. Although it is possible to keep the same resolution as the original image (see Tomotherapy user documentation), the imported kVCT image is usually down-sampled to the typical 256x256 grid (times the number of slices). However, for very large CT data sets, the user may choose to down-sample down to 128x128 because of computer memory limitations. Users may also consider removing slices using a DICOM editor. It is important here to

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remember that the selection of the dose calculation resolution grid selection will work the same way, whatever the resolution of the kVCT image after importation. Therefore, a normal dose grid will compute dose on 128x128 voxels for a 256x256 imported image and on 64x64 voxels for a 128x128 imported image. Therefore, if a normal dose calculation grid is the usual setting in a given centre, we recommend using the fine calculation resolution if the original image was down-sampled down to 128x128 to keep the same overall calculation resolution for both a 256x256 and 128x128 imported KVCT image.

The clinical impact of the chosen resolution depends on target volume size and shape, prescription levels and the location of organs-at-risk relative to the target volumes. The dose calculation time scales with the number of voxels.

6.1.4 TomoHelical delivery

Helical Tomotherapy has unique delivery settings due to the combined use of CT architecture and a binary multileaf collimator (MLC). Treatment parameters are the slit width, the pitch and the modulation factor. As mentioned before, three commissioned slit widths are typically available (5, 2.5 and 1 cm). The size of the slits controls both the speed and longitudinal conformity. Everything else being equal, the treatment time is roughly inversely proportional to the selected slit width. Therefore, faster treatment time may be obtained using larger slit widths but at the cost of a degraded longitudinal conformity, except for the superior-inferior dose build towards a target volume due to the dynamic properties of the collimation system as available in TomoEdge.

The pitch is defined as the ratio of the couch displacement for one gantry rotation to the slit width. Because of the translation of the couch across the longitudinal field, ‘helical beam junctioning’ effects may occur (the ‘thread’ effect), especially off-axis because of the divergence of the beam. Those effects result in ‘ripples’ in the dose distribution, more or less pronounced depending on the off-axis distance (for a slit width of 2.5, the magnitude of the ripples is limited to 3% for pitches lower than 0.5). Kissick et al (M W Kissick et al., 2005) provided a simple formula from both experimental and theoretical data to minimize the magnitude of those ripples, that is, selected pitches should follow a rule 0.86/n where n is an integer larger than one. A more complete theoretical approach of the thread effect may be found in Chen (M. Chen et al., 2011). Smaller pitches enable less significant thread effect. Therefore, one should consider using smaller pitches for tumours located off-axis if the thread effect is a concern. In versions 4.x and higher, the machine isocentre may be easily moved during treatment planning to minimize the thread effect. More quantitative information may be found in the aforementioned references.

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However, small pitches may lead to shorter leaf opening times since a given transversal slice will be longer within the aperture or slit opening and a voxel within this slice may therefore be exposed during more gantry rotations. Inaccuracies in the modelling of leaf latencies may increase dose inaccuracy for short leaf opening times as shown by Westerly (Westerly et al., 2009). Pitch values should be selected such that the gantry period is higher than 12 s (minimum allowed period). To allow higher pitches without a significant thread effect, the tumour target volume should be placed close to the isocentre of the machine.

The modulation factor is defined as the longest leaf opening time divided by the average of all nonzero leaf opening times. Since the modulation factor provided by the user is the maximum one allowed for the optimizer, the final modulation factors obtained at the end of the planning process will, in general, be lower. A higher modulation factor may result in a longer maximum leaf opening time, which is related to the treatment time. On the other hand, a higher modulation factor allows a larger range of beamlet intensity levels to the optimizer.

The gantry rotation period is automatically selected by the system as the fastest gantry speed possible to achieve the desired dose prescription. However, there are a few constraints. The gantry period can take values between 12 s (for versions 4.x or versions 1.x on TomoHD) and 60 s.

The treatment dynamics may influence outcome for mobile tumours because of the potential interference between beam and patient motions, i.e. the so-called ‘interplay effect’. For one single fraction, this effect has been shown to be relatively moderate both theoretically (Kissick et al., 2008; Michael W Kissick et al., 2005) and using 4D Monte Carlo simulations where deviations of maximum 4.4% (D_{95}, single fraction) were observed for a small lung tumour with a large motion amplitude (Edmond Sterpin et al., 2012a; Wanet et al., 2014). The interplay effect can be further minimized using slow scan speeds. Moreover, it tends to average out for multiple fractions. Techniques to ensure regular breathing (e.g. by audio-coaching) may also mitigate the interplay effect.

6.1.5 Additional specificities of TomoDirect delivery

In TomoDirect (only available in version 4 and higher or version 1.x or higher of TomoHD), pitch has no longer a meaning since there is no gantry rotation, although it keeps the same name in the TPS. The ‘pitch’ here is the couch distance travelled per projection, projection being defined here as the interval of time for each control point of the MLC. The system sets the pitch by default to one tenth of the slit width. The user can also choose several fields with arbitrary gantry angles and attach each one of them to the target volume of his choice. Moreover, the transverse size of the fields is set by default to only cover the target volume

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but can be enlarged by the user (which is useful for breast irradiation). In terms of quality assurance, one major difference with helical delivery is the potential higher sensitivity of treatment accuracy with output stability with gantry position. In continuous gantry rotation, variations in output may cancel each other as long those follow a periodic pattern. For Tomotherapy systems equipped with the Dose Control System (*DCS*), the static and rotational output is stabilized. The non-rotational nature of TomoDirect makes calculation accuracy more sensitive to the position of the Accuray treatment couch in the kVCT image for some angles of the gantry. The TPS warns the user when accuracy may be significantly sensitive to the exact position of the treatment couch. Since it is very difficult to reproduce from planning to treatment the position of the patient with respect to the treatment couch, we do not recommend overruling the TPS warning.

6.1.6 3DCRT

For both TomoHelical and TomoDirect, there is the 3DCRT option available. Briefly, 3DCRT is a very simplified IMRT procedure that does not allow interactive optimization. The user can only block some organs at risk, improve homogeneity to target structures and force normal tissue homogeneity (no hot spots). For the latter, an external contour (patient outline) with the label ‘external’ must be available. The optimization consists of one single iteration. Because of the very unlikely use of this feature in European facilities, the QA of this option is disregarded in the current report.

6.1.7 Optimization on non-GPU systems

When the beam parameters specified above are defined, the user may select the optimization panel, define the constraints and start the optimization process. For current versions up to version 4 and TomoHD systems included, the user can choose between three optimization options: ‘TERMA’, ‘beamlet’ and ‘full scatter’. Before moving to EOP (section 6.1.9), the user must perform a ‘get full dose’ iteration, which calls the same algorithm as in full scatter optimization mode. TERMA optimizes dose distributions fast by disregarding during the dose computation process the convolution of the TERMA with the energy-deposition kernels. However, such an optimization scheme does not provide acceptable accuracy of the dose distributions and can only be used as an initial guess or for a very fast optimization for emergency/palliative cases as is the case in the StatRT.

The most typical optimization workflow starts with the ‘beamlet’ optimization mode. The workflow is illustrated in Figure 6.2. In the ‘beamlet’ optimization mode, the impinging fluence, modulated by the MLC, is modelled as beamlets (single element of a beam used

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during optimization) around the control points of the MLC (projections). The beamlets intersecting the target volumes, with an initial weight of unity, are pre-computed in a range of a fraction of an hour to several hours depending on the computer hardware installed and the size of the PTV. When the pre-computation is completed, fast optimization (typically a few seconds per iteration) of the weights of each beamlet may be performed. Depending on the versions of the software, dose calculation and beam modelling can be different. Table 6.1 summarizes some of the differences between versions that may impact planning quality and user experience. In version 2.x, beamlets are compressed and truncated (low dose threshold), that is, energy is not strictly conserved. The compression of the beamlets is needed for storage. Moreover, the MLC is assumed to be ideal without taking into account tongue-and-groove and LFOF. Versions 3.x include more information in the compressed beamlets while versions 4.x use a beamlet compression technique that conserves the mean energy. Moreover, LFOF and a square leaf filter are included during beamlet optimization in versions 4.x for Hi-Art and versions 1.x for TomoHD.

Optimization in full-scatter mode computes the dose for all iterations like a ‘get full dose’ iteration. It is seldom used, because of the significant time needed for each iteration (typically around 2 min on most systems around the year 2015). The level of complexity of the full dose computation changed significantly with the versions, as summarized in Table 6.1. In versions 2.x, MLC details were not taken into account implicitly during dose calculation in full scatter. However, the full beamlet information is used. This results in a higher dose to all structures. Dose is renormalized to match the prescription point for the target volume. However, the user may still notice an, usually small, change of DVHs between the final beamlet optimization iteration and a get full dose iteration with a slight modification of the dose to critical structures. In versions 3.x, the MLC is still assumed as ideal during a ‘get full dose’ iteration. Starting from version 4.x,TomoHD systems with a mint drive installed, all the available MLC details are implicitly included during dose calculation through a leaf filter that contains tongue-and-groove, realistic penumbra and LFOF information. In versions 4.1.x and later, the gantry rotation is super sampled with 153 positions of the gantry per rotation instead of 51. Taking into account more gantry positions may have a significant impact for small off-axis targets with small modulation factor (Edmond Sterpin et al., 2012c; Tudor and Thomas, 2013). Before version 4.1.x, the effect of continuous rotation, if any, may only appear during DQA with differences between measurements and C/S, especially at the edges of the tumour volume. In version 4.1.x and later, degradation of the DVH may occur after a ‘get full dose

iteration’ because of the super sampling of the gantry positions.

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Table 6.1 Summary of relevant features for different versions of the TPS software for treatment plan optimization and dose calculation (CPU systems).

Version 2.x	**Version 3.x**	**Version 4.0.x**	**Version 4.1.x and up** **Version TomoHD 1.x and up**
Beamlet pre-computation			
Compression and truncation	Compression and truncation (more information)	Compression with mean energy conservation	
Beamlet iteration			
Ideal MLC		LFOF (square leaf-filter)	
Get full dose - full scatter iteration			
No MLC details		Full MLC modelling (leaf-filter)	Full MLC modelling (leaf-filter). 153 gantry angles
End-of-planning			
Remove small leaf opening times. Additional MLC details (including leaf latencies) in procedure sinogram		Remove small leaf opening times. MLC details implicitly included. Leaf latencies incorporated in procedure sinogram	

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6.1.8 Optimization on GPU-systems (VoLO)

In GPU-systems (Chen et al., 2012; Lu, 2010), the workflow is essentially the same, except that there is no beamlet pre-computation anymore. Nine iterations over ten are computed using a fast pencil-beam algorithm (Lu and Chen, 2010). One iteration over ten is performed in full scatter mode, with 153 gantry angles. For a wide set of target sizes and off-axis positioning, this ensures that discretization of gantry motion in the TPS has no significant impact on accuracy (Hardcastle et al., 2012; Edmond Sterpin et al., 2012c; Tudor and Thomas, 2013). Following this workflow, the 'get Full Dose' step will therefore bring no modification to the dose calculation obtained after the last full scatter iteration.

TomoEdge is available only on systems equipped with VoLO dose calculation algorithm.

It is important to note that convolution kernels are not stored as such like in CPU systems but fitted with two exponentials. Chen et al (Chen et al., 2012) has shown that this approximation does not impact significantly dose calculation accuracy.

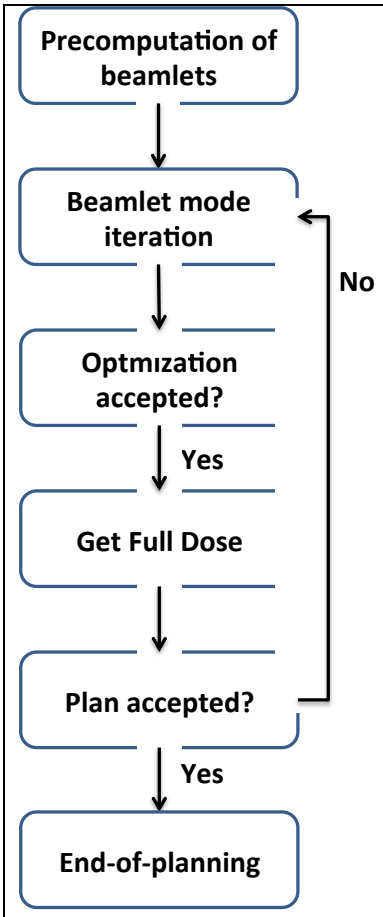

Figure 6.2 Typical workflow of treatment plan optimization and plan acceptance for non-GPU Tomotherapy TPS

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6.1.9 End-of-planning (EOP)

During EOP, the TPS performs two operations. Treatment fractions are generated ('fractionation') and final dose calculation is performed. During fractionation, the gantry period is actually determined. An illustration of the sequences performed during EOP is shown in Figure 6.3, with the specificities of each version of the TPS software.

In all versions, the EOP dose calculation performs most of the operations of the 'get full dose' but after removing very small leaf opening times (< 20 ms) from the sinogram. This may result in minor modifications of the DVHs, usually a slight decrease of dose to some volumes.

In the EOP process, 'procedure sinograms' are created from 'optimization sinograms'. The 'procedure sinograms' correct for most of the MLC details not included during optimization. In versions 2.x and 3.x, the MLC was assumed as ideal during optimization. During fractionation, T&G and LFOF information are included in the sinogram in such a way that the MLC will effectively reproduce the ideal behaviour assumed during optimization. On the other hand, such operations are not necessary for versions 4.x and TomoHD systems since MLC details were already included during the 'get full dose' operation.

One last effect to take into account is the leaf latencies. Leaf latencies are modelled in the Tomotherapy TPS by assuming the relationship between the actual and planned leaf open times is linear. The exact nature of this relationship is empirically determined by using the MVCT detectors to measure actual leaf open times as a function of programmed leaf open times for eight MLC leaves at projection intervals ranging from 200 to 1000 ms and between 10-90% of the total projection interval. The use of a larger (than the minimal) gantry period (can be accomplished by choosing a larger pitch), increases the fidelity of leaf openings by increasing the range of leaf open times that fall in the linear region of the latency curve. A large number of small leaf open times give rise to dose inaccuracies which can be measured in a DQA measurement (Westerly et al., 2009). Leaf latencies corrections can only be computed during fractionation because the final gantry rotation period must be known to apply the correction. In versions 2.x and 3.x, leaf latencies are not taken into account during final dose calculation. As it was the case for other MLC details, the leaf latency correction is included in the 'procedure sinogram' such that during actual treatment, the MLC effectively reproduces the ideal behaviour as assumed during optimization and EOP. In version 4.x and TomoHD systems, it is different. EOP computes dose distributions directly from 'procedure sinograms'. Hence, EOP dose includes corrections for leaf latencies implicitly during dose calculation. However, the operation is neutral in terms of dose distributions. Leaf latency correction is performed to create the procedure sinogram and the inverse of the same

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correction is applied during EOP. However, since the procedure sinogram can now directly be used for dose computation, a change in leaf latencies (because of a replacement of the MLC, for instance) may be reflected in the dose distributions. This will unlikely happen during the preparation of a treatment (the MLC data should change between get full dose operation and EOP), but may occur if a DQA dose calculation is performed days after the preparation of the treatment. This has the advantage that a user may analyse the effect of a change in leaf latencies parameters on the dose distributions using the DQA tool provided (see paragraph 3.1 and 6.2.2).

Finally, another minor difference between EOP and 'get full dose' for all versions is the computation of dose in the air surrounding the patient body contour. Therefore, isodose curves appear outside the body volume, which is not the case for dose distributions obtained during optimization.

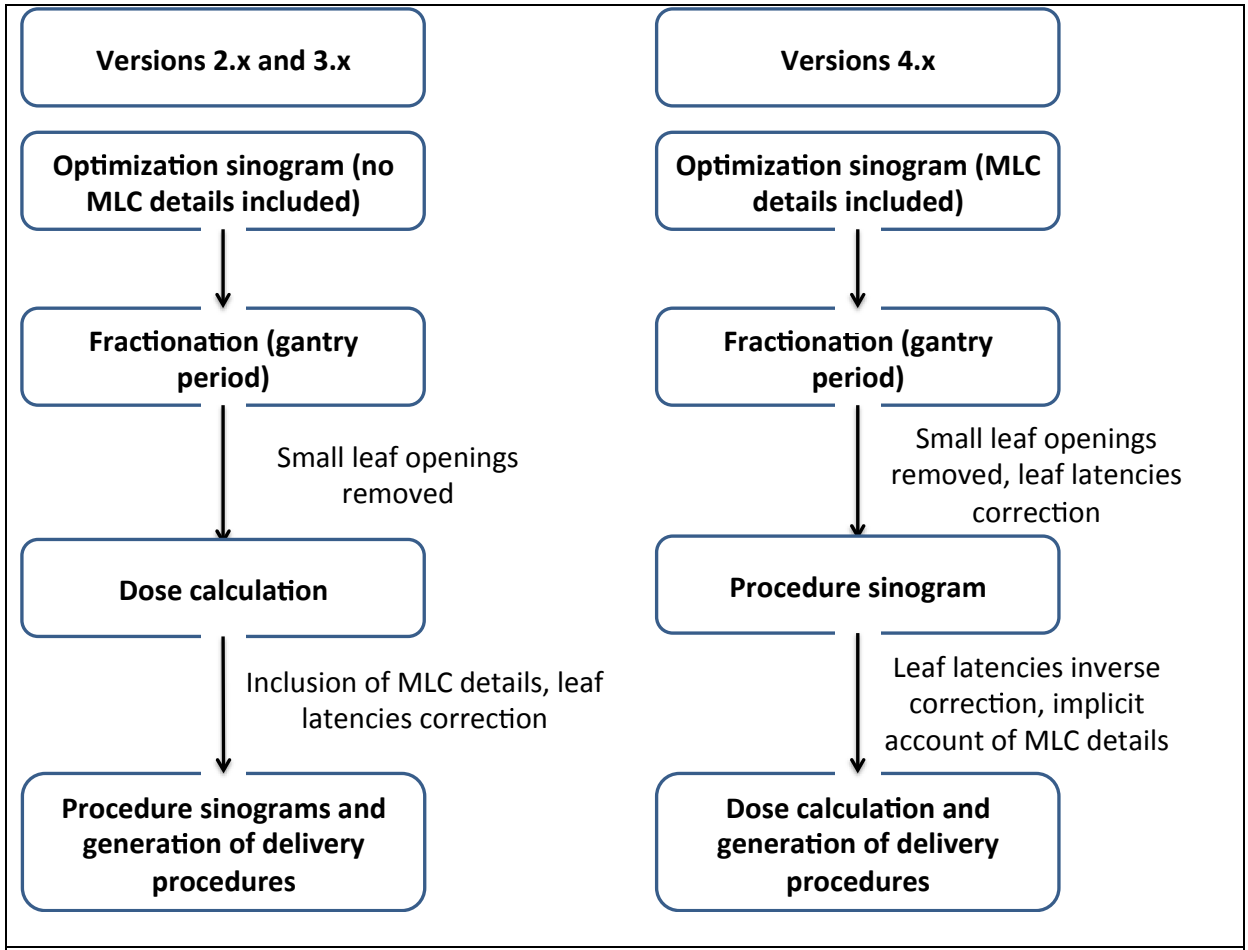

Figure 6.3 Sequence of operations performed during the EOP process depending on the version of the Tomotherapy TPS.

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6.2 Quality assurance of Tomotherapy treatment planning

For Tomotherapy the philosophy is to tune each new machine to the gold standard. Still, proper quality assurance needs to be performed carefully, both globally and patient-by-patient.

6.2.1 kVCT image and IVDT

The consistency of CT information throughout the CT acquisition, contour delineation, treatment planning and treatment delivery processes must be guaranteed as for any other TPS. Table 3.2 of TG-53 (Fraass et al., 1998) lists image information consistency tests that should be performed. Information may also be found in NCS report 15 (Netherlands Commission on Radiation Dosimetry, 2005). A well-defined phantom may be used for this task. Hounsfield units, number of pixels, pixel sizes, slice thickness and image size must be verified. Geometrical location and image orientation consistency between CT scanner and the TPS must be ensured as well for all allowed scan orientations, such as head first supine, feet first supine, head first prone and feet first prone. The transfer of contours and structures from third-party software must be checked thoroughly. It can be performed using a phantom with structures of known sizes and locations.

The conversion of CT number (Hounsfield Unit) to mass density can be performed using the proper IVDT. IVDT uses linear interpolation between known couples HU - mass densities. Important is to insert a proper value for the HU value for air to avoid reconstruction artefacts in the outer regions of the FOV. Those couples may be acquired on a given CT scanner with the standard cylindrical ‘Solid Water’ phantom provided with every Tomotherapy unit with the inserts of different densities (provided in the QA package). The consistency between the CT (or MVCT) scanner procedure used for image acquisition and the IVDT selected for treatment planning must be ensured for every patient.

The uncertainties of the actual densities of the inserts and the interpolation may cause discrepancies between the converted mass density and the actual value close to water. Since the patient is mainly a water-like medium, this may cause differences between computed and delivered dose distributions that cannot be detected during quality assurance of dose distributions in a homogeneous phantom. Ideally, a water point (mass density of 1 g/cm^3) should be defined with the best accuracy achievable. One way to perform this operation is to scan a rectangular water tank filled with water. Currently Tomotherapy systems are shipped with a real water insert for the Cheese Phantom. The obtained HU number can then be associated with a mass density of 1 g/cm^3. When acquiring the IVDT curve with the standard cylindrical Solid Water phantom with multiple inserts of various

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densities, we do not recommend using inserts with densities close to water (within ±100 HU). For a detailed description see chapter 7.1.5.
All tests related to kVCT geometry should be performed annually and after an upgrade and/or an update of the system related to CT acquisition and transfer.

6.2.2 General dosimetric validation and QA

Tomotherapy TPS implicitly generates IMRT plans. The manufacturer implemented a QA module into the TPS called ‘DQA’ (‘Delivery Quality Assurance’). This module allows the user to compute dose distributions with the same set of treatment plan parameters, like sinogram, jaw settings, couch speed, gantry period etc, used during the planning phase, with a phantom of user’s choice. The standard cylindrical Solid Water phantom distributed with each Tomotherapy unit allows placing films and ionisation chambers in various positions. Other phantoms from other vendors (for a list see chapter 3.1) are also well suited for treatment planning verification. Measured and computed dose distributions may be compared for ionisation chamber measurements or after film processing in the DQA module. Gamma-analysis of differences between computed and measured dose distributions may be performed as well.
For general dosimetric QA of the TPS, one may use the standard treatment plans generated by the vendor made on the cheese phantom (former called ‘TomoPhant 5 sets’), with a cylindrical dose distribution on-axis and off-axis for all the commissioned field widths. Similar standard treatment plans may be generated for TomoDirect and TomoEdge plans for all commissioned field widths. The user may also define other treatment plans to his convenience, with on-axis or off-axis targets and various sizes. However, for general dosimetric QA, it is recommended to use simple geometries with homogeneous doses on sufficiently large volumes (i.e. much larger than the size of the ionisation chamber) to avoid strong influence of the position of the detectors in the homogeneous region. More extreme configurations like targets close to the phantom surface (within build-up, build-down regions) should be avoided. A ‘normal’ or ‘fine’ calculation grid resolution should be chosen. Ion chamber measurements should be performed in high-dose and low-dose regions. For verification of dose-gradients, films are better suited. For the homogeneous dose regions, during commissioning of the machine, an acceptance criterion of 3% for TomoHelical deliveries and 4% for TomoDirect deliveries in homogeneous regions are recommended. With *DCS* enabled, the output of TomoDirect is more stable for all angles and thus the recommended tolerance is also 3%. Any systematic deviation from these acceptance criteria during daily, monthly or annual checks should be investigated. A difference of more than 5%

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requires an immediate action. In high dose-gradients, a 3 mm spatial agreement criterion is recommended as stated by Van Dyk (Van Dyk, 2008; Van Dyk et al., 1993) and TG-119 report (Ezzell et al., 2009). Dosimetric verification of helical standard treatment plans should be performed weekly for one configuration (2.5 cm field size, off-axis target) and after any upgrade/update of the TPS for all commissioned field sizes.

A modification of the MLC should be followed by a dosimetric validation for all commissioned fields to check proper accounting for newly generated MLC and leaf latencies data. In that case, new optimization and generation of the treatment plans or the use of the 'Transfer' application (chapter 3.2.5), should be performed to force the sinograms to take into account modifications of MLC data. Measured differences between procedures generated with the old MLC model and the new treatment plans should be within tolerances to ensure consistency of treatment delivery for patients currently undergoing their therapy. The number of procedures selected to undergo this additional QA is at the discretion of the MPE.

At the time of the present report, there is treatment planning QA specific to the TomoEdge feature. The latter is verified in regular plans by checking the penumbra in the longitudinal direction. Research is welcome to design QA tests of the treatment planning system that would be sensitive and specific to the modelling of the jaws.

The accuracy of the C/S algorithm regarding inhomogeneity corrections should be assessed as well. Anthropomorphic or homemade phantoms are suited for that purpose. Several examples of inhomogeneous phantoms and potential test configurations may be found in literature (Ardu et al., 2011; Zhao et al., 2008) .

6.2.3 Patient-specific delivery QA (DQA)

For patient-specific DQA, there is no significant difference in the methodology than the one described in Figure 6.4. However, since generated dose distributions are often more complex than in standard treatment plans ('TomoPhant 5 sets'), the acceptance criteria should be adapted. It has been historically recommended to perform patient specific QA with measurements for each patient-plan. This requirement involves a significant workload, which may be more difficult to justify for some centres that observe no significant deviations between planned and measured dose distributions for years of operation. Thus, other approaches might be considered like a random selection of the treatment plans subject to QA and also the introduction of software-based patient specific QA (Handsfield et al., 2014; Siochi et al., 2013).

Accepted criteria provided in literature for IMRT plans should also be used for Tomotherapy. Gamma analysis with acceptance criteria 3% in dose and 3 mm in distance (3%/3mm),

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global dose difference, are often recommended in literature (Ezzell et al., 2009; NCS 22, 2013). Venselaar et al (Venselaar et al., 2001) proposed also a 4%/3 mm criterion in high dose regions and high-dose gradients, respectively, and a 5% tolerance in low dose regions. From various publications and the experience of the NCS subcommittee, the recommended tolerance for chambers placed in homogeneous regions is 3% of prescribed dose. Gamma-analysis comparing computed and measured dose distributions using film should be performed with a 3%/3 mm criteria with a passing rate of 90%, using at least a 'normal' calculation grid resolution. The average gamma value is also a good metric for quantifying differences between measured and calculated dose distributions. We recommend an average gamma value below 0.5 (or preferably 0.3). Up to version 5.x, it is not possible to define in the DQA a ROI for gamma-analysis. Therefore, points not relevant for evaluating treatment plan quality (e.g. points outside phantom geometry) are taken into account. A visual inspection of gamma-results may determine if points failing gamma-test are originating mostly from those outlying points. Ideally, third-party software where ROIs can be defined should be used. Film dose may be scaled to the value obtained with ionisation chamber readings. Another method for normalization of film dose was described by Thomas (Thomas et al., 2005a), which can be implemented as long ionisation chamber readings shows acceptable deviations in homogeneous regions. For arrays, one could use acceptance criteria from the following references (Geurts et al., 2009; Jursinic et al., 2010; Van Esch et al., 2007; Xu et al., 2010).

Discrepancies larger than 5% for point measurements in homogeneous regions should lead to immediate investigation before patient treatment. Discrepancies higher than 3% but below 5% and gamma-passing rate below 90% should be investigated but the treatment may be started/continued, at the discretion of the physicist and/or physician. The decision depends mainly on the position of the chambers with respect to dose distribution and the number of readings out of tolerance. Visual inspection of comparisons of measured and computed dose profiles may also help diagnosis. The discrepancies may have several origins: phantom setup errors, chambers placed close to high dose-gradients, machine output stability, machine output drift, energy drift, thread effect etc. As mentioned in section 6.1.5, dose calculation accuracy versus measurements may be compromised by small leaf-opening times (small pitches). A re-optimization of the treatment plan with a higher pitch might be worth doing if all aforementioned potential issues were not the cause of the considered discrepancy. It is important to determine if the discrepancies observed are either general or specific to the patient treatment plan. The standard treatment plans mentioned in Figure 6.4

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may be used for that purpose. A verification of machine output using an msr static field is also to be considered if the deviations with standard treatment plans are out of tolerances.

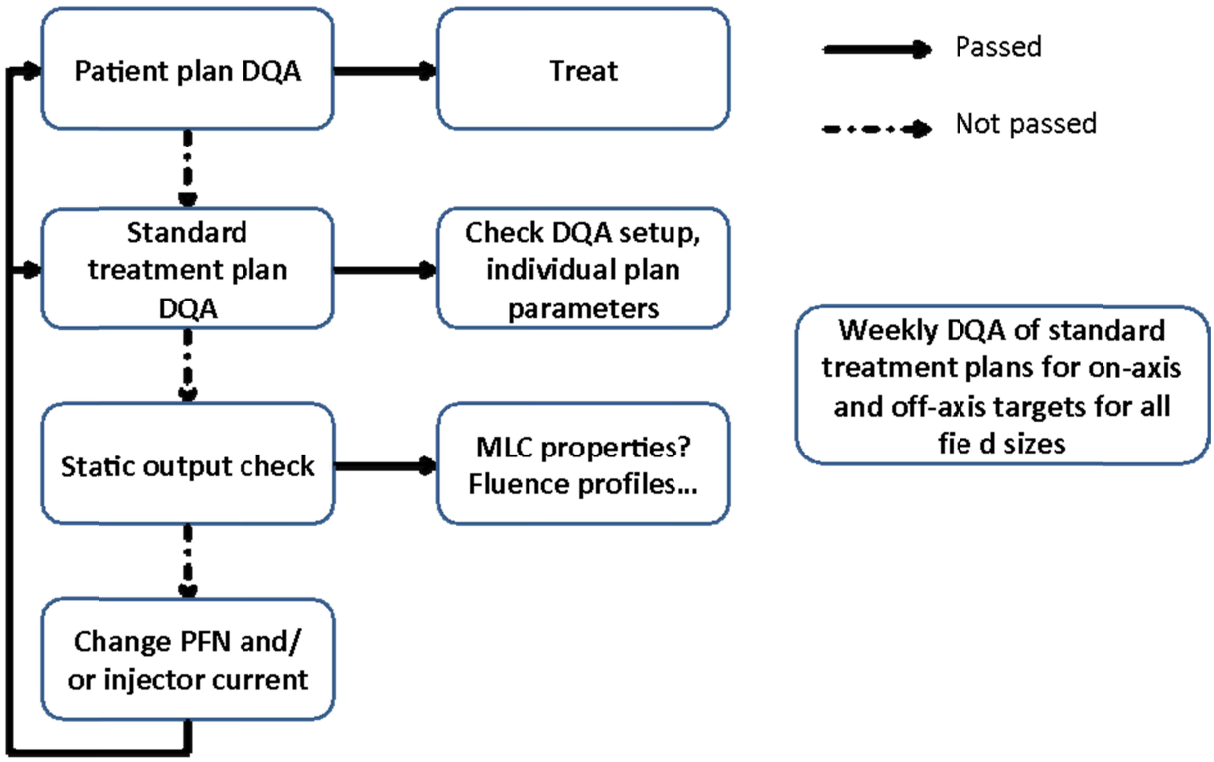

Figure 6.4 Workflow for general dosimetric QA and patient-specific QA. Solid lines refer to action when QA tests succeed while broken lines correspond to unsuccessful tests. More than 5% dose errors in homogeneous dose regions requires immediate action. When standard treatment plan DQA fails by more than 5%, all treatments should be delayed until the source of discrepancies is corrected.

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7 Patient Transfer and Planned Adaptive

7.1 Introduction

The Tomotherapy machines are tuned to provide dose profiles that agree with the 'Gold standard'. However, given an identical sinogram, differences in dynamic properties between machines will give rise to differences in delivered fluence and therefore dose. When a patient needs to be treated on a Tomotherapy machine which is not the machine were the dose planning sinogram is generated, this sinogram needs to be transferred from one machine (source) to the other (destination). In this transfer, differences in machine properties are taken into account. A dedicated software tool for patient transfer (Data Manager DMS) is provided by Accuray. This tool scales the sinogram which is generated for the source machine to a new patient sinogram for the destination machine such that the fluence on the destination machine matches the original one closely. After this rescaling a final dose calculation is performed using the rescaled sinogram and using machine properties of the destination machine. Dose distributions of source and destination can be compared.

The new sinogram is stored in the database of the source machine only after approval of the new dose distribution. After this, the patient is archived and subsequently restored on the destination machine.

The number of fractions already administered on the source machine is stored and the remaining fractions will be available on the destination machine. As both machines have an individual patient data base, the treatment history is not shared. Thus, there is a risk that transferred patients might be administered too many fractions when treated with the plan on the source machine. To avoid this problem, Accuray recommends deleting the patient file on the source machine after transfer. In that way, one needs to re-transfer to enable a fraction delivery on the source machine. If the plan should be available on both machines at the same time, local procedures are required for manual administration of delivered fractions to keep track of the treatment history. Note that Accuray is planning to provide a shared database to improve this situation (iDMS database Radixact system).

7.1.1 Validating the Patient Transfer system

To validate the Patient Transfer system for first time use, it is advised to check the deliverability of the transferred sinogram on the destination machine for a limited number of patients. For this a measurement at the destination machine of the transferred DQA sinogram should be compared against the DQA measurement performed at the source

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machine. Differences between dose distributions should be within tolerances stated in section 7.1.3.

7.1.2 Sinogram scaling

The properties that needs scaling are leaf fluence output factors (LFOF), dose rate, leaf latency values and jaw output factors. The system scales the leaf open times and adjusts the pitch and gantry period (taking care of jaw size differences) to obtain equivalent dose distributions (Zhuang et al., 2009).

Modifying individual leaf open times compensates for differences in LFOFs. Differences in dose rate can be corrected by a global scaling of all leaf open times. After scaling, some leaves may have an open time below the threshold (20 ms) and will not open anymore. Potentially this can lead to a different dose distribution. This may be assessed after final dose computation and by comparison of the original and transferred dose distributions.

If the field width is not identical on source and destination machines, the pitch is rescaled using the relation: $\mathrm{pitch}_{\mathrm{dest}} = \mathrm{pitch}_{\mathrm{source}} \frac{\mathrm{FWHM}_{\mathrm{source}}}{\mathrm{FWHM}_{\mathrm{dest}}}$ to ensure that the helical delivery of fluence remains the same. The rotation period can change as a result of the sinogram scaling, leading to a different treatment time for the destination machine.

There are a number of factors that are not taken into account in the transfer software, namely differences in beam energy, beam profile and cut-off thresholding of leaves (Zhuang et al., 2009). As mentioned above, it is assumed all machines are currently tuned to agree with a Gold Standard, so that the impact of beam energy and beam profiles should be negligible.

7.1.3 QA of patient transfer

It is important to ensure that the most recent values of the dynamic parameters of the destination machine are available in the source machine database to enable accurate sinogram recalculation. Therefore the most recent machine properties of the destination machine should be archived and made available to the source machine. Accuray provides a clear prescription how to achieve this. To approve the new dose distribution, one should analyse differences between source and target dose distributions in the Data Manager software.

Tolerance: 97% of the volume of a selected structure should have a dose difference smaller than 2%. This can be verified in the dose comparison dialog in DMS using the ‘relative difference DVH’ display. If this is not achieved, the responsible MPE should be consulted.

Comment: An older version of the transfer tool (PTS 2.2.2) was evaluated statistically by

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Zhuang et al (Zhuang et al., 2009). At that time the Tomotherapy machines were not yet tuned to agree with the Gold standard. Dose differences were evaluated in the target and in organs at risk. Depending on the transfer direction (Tomo1 to Tomo2 or vice versa) systematic dose differences of 0.8 % in the target volume and 0.7 % in normal tissues were obtained, with outliers up to 2 %. As stated above, at present these effects should be much smaller because of the Gold Standard.

7.1.4 Planned Adaptive

During a radiotherapy treatment of several weeks the shape and location of internal organs and/or the shape of the body contour may change due to tumour shrinkage, variations in for example bladder and rectum filling or by weight loss. Well-known examples are the position and volume of the parotids for head and neck patients and the shrinkage of tumour volume for gynaecology patients causing organs at risk to move into the treatment field (Le Tinier et al., 2012)). For some patients the effect may be considerable and warrant a new treatment plan for the remaining fractions. To maximise consistency in the decisions, the medical physics expert and physician should decide on criteria for re-planning, based on observed changes in anatomy and dose differences, taking into consideration the systematic or random nature of these changes.

Adaptive radiotherapy allows assessment of the dosimetric impact of anatomical changes during the course of treatment. Planned Adaptive is a tool to support decisions on corrective actions with the aim to obtain a clinically delivered dose distribution as close as possible to the planned one. The tool supports the viewing of the match results of the MVCT with the planning CT and also to perform the match again. Since the registration can be modified, several patient positions can be simulated and the impact on the dose distribution can be evaluated.

The tool supports manual correction of the planning CT structures and the viewing of differences between planning- and the verification contours. Furthermore, using the planning sinogram and the MVCT, the actually delivered dose can be calculated in the patient geometry. Differences in planned and delivered dose distribution can be evaluated using DVH tools and dose –difference- distributions in orthogonal planes.

This procedure can be used for each fraction and doses can be summed. Planned Adaptive, as described here, does not use deformable registration, therefore a consistent voxel dose tracking per structure is not supported.

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Voxels within a structure can be selected based on the received dose. A new structure can be defined based on these MVCT voxels and the planning optimization process can be restarted with this new structure as extra input.
For full re-planning a new kVCT image can be made but it is also possible to use the latest MVCT data, possibly using the new contours. If the FOV (fixed to 40 cm) of the used MVCT is smaller than the body contour, the original kVCT will be stitched for the missing tissue. Using the MVCT for re-planning demands a precise and recent calibration of the MVCT IVDT curve.
Note that Accuray provides a new adaptive tool called PreciseART, which include deformable registration and a workflow to support adaptive measures. This new product is not discussed in this report.

7.1.5 QA on Planned Adaptive

MVCT number calibration procedure for water/air:

Procedure: A MVCT-Number calibration procedure should be performed. This so-called 'MVCT linearity correction' procedure is provided by Accuray. The cheese phantom is placed isocentrically on the couch and a MVCT scan is performed. The MVCT image of the cheese phantom is used to measure two densities of interest: solid water and air. These values are processed fully automated as long as the measured values do not deviate significantly.
Parameter and tolerance: HU values within 30 HU of reference values
Interval: monthly or weekly if a rotating target is used.
Comments: One should take care that the imaging beam is included in the *DCS* calibration process.

Validation of the MVCT IVDT table

Procedure: A MVCT scan of a large enough phantom containing homogeneous regions with densities covering the range from lung equivalent to compact bone is acquired. For a correct representation of materials with a high Z number, additional regions (plugs) with adequate compositions might be required. In clinical practice the anatomical objects (implants) with high Z are given a 'directional block' during optimization phase, to avoid that radiation will pass this implant before is enters the PTV. The value of 1 g per cm^3 (water) should be measured with real water. The introduction of the non-rotating target and *DCS* greatly stabilized the drift in HU. It is assumed all Tomotherapy systems are now equipped with these improvements.

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A ROI is drawn in every region and the mean value is reported and compared with the values stored in the MVCT IVDT. Of course, the same care should be taken to measure and maintain the kVCT planning CT IVDT which is used for planning dose calculation. See also chapter 6.2.1.

Parameter and tolerance:

The water-equivalent materials should be within 30 HU from the reference and the lung and bonelike materials should be within 50 HU from the reference (Langen et al., 2010, 2005a).

Interval: If the MVCT scans are used for dose calculation, the check should be performed monthly or weekly when using a rotating target, depending on target condition. If the fixed target is installed an annual check or after target or linac change suffices

Comment: Deviations in the HU values in the order of the tolerances can result in dose uncertainties in the order of 2% (Langen et al., 2010). When the HU values of water and air are out of tolerance, this should be corrected. This is done either by editing the IVDT table in the Planning- and Planned Adaptive software, or by following the 'MVCT linearity correction' procedure provided by Accuray and described above. If the MVCT is not used for dose computation, the HU unit validation may be omitted. The values in the MVCT image can be determined in any freeware image analysis tool, e.g. ImageJ.

The procedure can be evaluated by making a dose plan on an MVCT study of the cheese phantom, measuring the dose (e.g. with an ionisation chamber) and by comparing delivered dose with the planned dose. Result should be within 2% in a high dose, low dose gradient area. The measurement should be corrected for a possible dose rate deviation. Note this only checks the near water HU values of the MVCT IVDT.

This study should be imported in the Planned Adaptive tool and again the dose is calculated on the phantom. The obtained dose distributions should be identical to the one found in the planning station. This should be done for a limited number of patients, before Planned Adaptive is used clinically.

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Appendix

Daily QA items

Recommended daily QA items using TQA				
nr	**Item**	**Purpose**	**alert level 1 / 2**	**Module**
1	Output MC1	Output machine raw and referenced	2% / 3%	Basic Dosim. System Monitor Daily QA SWS SWH
2	MC1 offset	Signal during beam off	NA	Airscan
3	Exit det. signal offset average	Signal during beam off	NA	Airscan
4	Exit detector cone shape	Transversal profile raw and referenced	2% / 3%	Basic Dosim Daily QA SWS SWH
5	Exit detector cone shape variation during procedure	Ratio shoulders left/right to the centre	2%	Basic Dos. Daily QA SWS SWH
6	Output ramp up (pulse 30 ms)	# pulses to reach average output value	100% within 300 pulses	Basic Dos. System Monitor SWS SWH
7	Air scan	Calibration exit detect. as imaging system	NA	Airscan
8	Health signals	Monitoring of technical system parameters	NA	System monitor
Recommended daily QA items – NON TQA –				
nr	**Item**	**Purpose**	**alert level 1 / 2**	**Module**
9	Overlap red and green lasers	Drift in laser line position	1 / 2 mm	NA

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Weekly QA items

Recommended Weekly QA items using TQA				
nr	**Item**	**Purpose**	**alert level 1 / 2**	**Module**
1	Output MC1 per pulse (3 or 30 ms)	Output stability during a procedure	2 / 3%	Daily QA SWS SWH
2	MonCh dose1/dose2	Change in beam energy spectrum	1%	System Monitor
3	Beam energy - PDD	Beam quality	1 / 2%	SWS SWH
4	Cone shape per pulse (3 or 30 ms)	Stability cone shape	2 / 3%	Daily QA SWS
5	Stability jaw collimation (see Monthly nr 4)	Variation in J7/J48 exit det. signal ratio	>0.4 mm	Daily QA
6	Field width constancy	Step wedge transmission profile	1.5 / 3.0%	SWS
7	Jaw Sweep	Dynamic behaviour of jaws (dyn. jaw det. offset constancy)	inf	Daily QA
8	Leaf Latency	Dynamic behaviour of leaves (Leaf open and leaf close projection time error)	5 / 20 ms	Daily QA
9	Air Pressure	Max. load air pressure system	Between 10 and 80 psi	Daily QA
10	IECx	Laser position in lateral position X	1 / 2 mm	SWS SWH
11	IECy	Laser position in longitudinal position Y	1 / 2 mm	SWS SWH
12	IECz	Laser position in vertical position Z	1 / 2 mm	SWS SWH
13	Couch speed	Relative ratio to reference	0.2 / 0.4%	SWS
14	MLC flash centre difference	Dynamic behavior of leaves	5 / 20 ms	SWH
15	MLC flash width difference	Dynamic behavior of leaves	5 / 20 ms	SWH
16	Gantry period difference	Dynamic behavior of the gantry	0.02 / 0.03%	SWH
17	Gantry phase angle difference	Number of projections phase shift	0.7 / 1.0º	SWH
Recommended Weekly QA items - NON TQA -				
nr	**Item**	**Purpose**	**alert level 1 / 2**	**Module**
Treatment Delivery for Tomotherapy				
18	Beam energy - PDD	Beam quality PDD 20/10	1 / 2%	NA
19	Beam output helical and static	Consistency with TPS pcsr using phantom and ionisation chamber	2 / 3%	NA
Megavoltage CT imaging system				

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20	HU CT number - only for rotating target	HU number consistency water and air	Within 30 HU water and 50 HU lung/bone	NA
21	Red and green laser overlap	Check of consistency of laser line position and orientation relative to each other	1 / 2 mm	NA
22	Set up correction accuracy	Red laser movement and couch correction	0.5 / 1 mm	NA

Monthly QA items

Recommended Monthly QA items using TQA				
nr	**Item**	**Purpose**	**alert level 1 / 2**	**Module**
1	'Exit det. average to Dose1' or 'Average fluence variation'	Drift MonCh vs exit detector	2 / 3%	Basic Dosim. Airscan Daily QA SWS SWH
2	Exit detector output signal	Stability exit detector central channels	2 / 3%	Basic Dos. Daily QA Airscan
3	Exit det. signal Average	Average stability	2 / 3%	Airscan
4	Jaw stability (see Weekly nr 5)	Jaw position variations (slit?)	≥0.4 mm	Air scan Daily QA
5	Jaw FOF J20	Fluence output factor J20	±10%	Jaw Sweep
6	Jaw FOF J14	Fluence output factor J14	±10%	Jaw Sweep
7	Jaw FOF J7	Fluence output factor J7	±10%	Jaw Sweep
8	Time skew	Speed of jaw response	inf	Jaw Sweep
9	Field width fixed	FWHM of the longitudinal profile for all slit sizes	±1% Gamma<1	Field Width fixed
10	Field width dynamic	FWHM of the longitudinal profile for a number of (a)symmetric slit sizes	±1% Gamma<1	Field width - dynamic jaws
Recommended Monthly QA items - NON TQA –				
nr	**Item**	**Purpose**	**alert level 1 / 2**	**Module**
11	Interrupted procedure	Check abutment completion procedure	1 / 2 mm	NA
12	Static output at 1 gantry angle	Output consistency	2 / 3%	NA
Megavoltage CT imaging system				
13	Virtual- to machine iso center	Virtual to machine iso centre consistency	0.5 / 1 mm	NA
14	Image quality	Noise	SD_{HU} = 35	NA

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			(typical)	
15	Image quality	Uniformity	SD_{HU} < 25	NA
16	Image quality	Resolution	1.6 mm	NA
17	Image quality	Contrast	Nr of visible plugs	NA
18	Image quality	Presence of artefacts	NA	NA
19	IVDT – only for rotating target	HU versus density	Within 30 HU water and 50 HU lung/bone	NA
20	MVCT dose	Dose per scan	< 3 cGy	NA
21	Gantry position	Roll correction	0.5 / 1º	SWH, other
22	Red laser reference point	Reference point positioning using red laser	0.5 / 1 mm	NA

Annual QA items

Recommended Annual QA items using TQA

nr	Item	Purpose	alert level 1 / 2	Module
1	Linac Transverse alignment	Alignment of linac in IEC X using MLC T&G	±0.34 mm	Linac Transverse Alignment Daily QA
2	Linac Transverse alignment during rotation	MLC T&G (full width quarter max cone centre: % out of focus)	±2% (empirically determined)	Daily QA
3	Jaw and exit detector alignment	Beam axis perpendicular to axis of rotation: Difference in FJ and BJ detector coverage	± 0.5 mm	Daily QA
4	IECy linac shift or IECy Source position	Alignment of linac with the collimator jaws	±0.3 mm	Linac Longitudinal Alignment Jaw Sweep/W

Recommended Annual or 'on indication' QA items -- NON TQA –

nr	Item	Purpose	alert level 1 / 2	Module
5	Y-axis beam centring and alignment	Alignment Y-jaw - beam plane – rotational axis, beam divergence and -twist	0.5 mm and 0.5°	NA
6	Treatment field centring (Only on indication)	Coincidence center positions field widths	0.5 mm	NA
7	MLC alignment	Leaf bank lateral position- and orientation relative to center of rotation	1.5 mm and 0.5°	NA
8	Cone profile	Check with beam model profile, measured in water	2%	NA
9	Longitudinal profile	Check with beam model profile, measured in water	1%	NA
10	Leakage	After replacement of shielding	0.3%	NA

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		material (mlc or linac change)		
11	Gantry rotation – couch translation	Synchronicity gantry-couch	1 mm	NA
12	Gantry angle – leaf dynamics	Synchronicity gantry-leaf	1°	NA
Dosimetry				
13	Reference dosimetry	PCSR field procedure	1%	NA
Megavoltage CT imaging system				
14	Orientation MVCT study	Correct orientation of scanned structures	NA	NA
15	Scaling, rotation, distortion	Correct scaling and orientation of a MVCT image stack	NA	NA
16	HU CT number	HU number consistency water and air	Within 30 HU water and 50 HU lung/bone	NA

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