PET-CT in Radiation Treatment Planning

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General

In recent years, technological advances in PET have made this modality increasingly interesting for its use to achieve more accurate radiation treatment planning. PET facilitates in the staging of many types of tumours, the identification of patients with distant metastasis, in tumour detection and discrimination, the improvement of consistent tumour delineation, and quantification of tumour characteristics. Therefore the use of PET, in addition to the anatomic information obtained with CT or MRI, helps to improve targeted radiotherapy. Furthermore, radiotherapy may benefit from the use of PET as a therapy response tool.

Incorporation of PET in radiation treatment planning is not free from pitfalls, however. In order to integrate PET into treatment planning for radiation oncology, logistical issues regarding patient setup, acquisition and reconstruction procedures, image fusion, target delineation, and technical and functional implementation in the clinic, must be addressed.

This chapter focuses on the basic quality controls for a combined PET-CT system when incorporating PET in radiation treatment planning. In essence, these tests are related to accurate repositioning of the patient on the different modalities being used. Inadequate repositioning may lead to a degraded planning accuracy, an inadequate dose to the tumour, an increased dose to normal tissue and an adaptation to false tumour characteristics. Special attention has to be paid to the co-registration of PET and CT. Localization errors and false-positives can be a consequence of inaccurate co-registration.

The quality controls that are described in the following sections provide a basis for using PET-CT in radiation treatment planning. However, additional issues such as patient preparation, optimization and protocolization of image acquisition and reconstruction, PET-based target definition, and a good collaboration between departments of nuclear medicine and radiation oncology, are also crucial when using PET-CT in radiation treatment planning. As logistics are complex, one has to accept a learning curve when incorporating PET.

In this chapter a distinction is made between (1) the situation where the CT-component of the hybrid system is used for radiotherapy treatment planning and (2) the situation where a stand-alone CT is used for treatment planning (often located in the radiation oncology department). When using hybrid PET-CT for radiotherapy treatment planning purposes, quality controls are more extensive.

Tables 1a and 1b give an overview of the recommended quality assurance (QA) tests, and corresponding test frequencies and tolerances. It should be remarked that these recommendations come from protocols that date from 2003 or earlier and that the currently installed systems are quite stable. The clinically implemented frequencies with which those QA tests should be performed, will depend on the specific properties of the used system, the specific clinical applications and the requirements of each individual department. Moreover, all recommended frequencies regarding the discussed tests are adaptive frequencies. I.e. it is recommended to start with the suggested frequencies, and to reduce the specific frequencies when the systems are seen to be stable. For more details regarding the specific tests in Tables 1a and 1b one is referred to the specific subsections.

Performance parameter	Description	Adaptive frequency*	Tolerance limits
Level and rigid table			
- Table levelness	Check table levelness at different positions on the table and in different directions (longitudinal direction vs. lateral direction)	Annually or after the system is serviced in a way that may have an impact on table levelness	Loaded table top: - longitudinal: 0,57° (2 mm per 200 mm) - lateral: 0,29° (2 mm per 400 mm) Unloaded table top: - longitudinal: 0,29°, 2 mm per 400 mm - lateral: 0,14° (2 mm per 800 mm)
- Table rigidity	Verify if table returns to its starting position after removing a load	Annually or after the system is serviced in a way that may have an impact on table rigidity	Deviation from starting position ≤1 mm
	Table fixation-mechanism rigidity	Each time the flat table top is mounted	The table should not move due to application of a small force
Table sagging	Table sag is measured with the table located at three different positions	Annually or after the system is serviced in a way that may have an impact on table sagging	Loaded table top: 0,57° (2 mm per 200 mm) Unloaded table top: 0,29° (2 mm per 400 mm)
Accurate table translation			
- Accuracy of longitudinal table motion	Check if table motion is orthogonal to the imaging plane	Monthly or when the daily laser QA tests reveal rotational problems	deviation ≤2 mm

- Accuracy of the digitally indicated longitudinal table motion	Verify that digitally indicated table motion agrees with measured value	Monthly†	deviation ≤2 mm
CT image matrix alignment	Verify that the imaged water surface in a phantom is horizontal	Annually or after the system is serviced in a way that may have an impact on this alignment	0,1°
Conversion of CT Hounsfield values to electron density	Verify that HUs agree with the values obtained at the time of scanner commissioning	Annually or after scanner re-calibration	- substantial deviation from the calibrated values or from the phantom manufacturer specifications‡ - the estimated Δ*HU* or the recommendations from literature‡

Table 1a. Specifications of the quality assurance measurements, recommended adaptive test frequencies and corresponding tolerance limits.

* As mentioned in the text, the recommended frequencies of the tests are adaptive frequencies. I.e., it is recommended to start with the suggested frequencies and, when appropriate, the frequencies can be adapted.

† The exact frequencies used may vary among institutes, as various clinical implementations exist (depending on the clinical scan protocol - on whether or not the external laser system and a fixed spacing between the external and internal lasers are used for patient localization). Hence, the exact requirements will be institute specific.

‡ The exact action level that will be most suitable depends on many items as is specified in the section "Conversion of the CT Hounsfield values to electron density". More details about the recommendations regarding these tolerance limits can be found in subparagraph 7 of this section.

Δ*HU* is the estimated HU range using equation (2) as described in the specific section.

Performance parameter	Description	Adaptive frequency*	Tolerance limits
Laser alignment accuracy			
Alignment gantry/external lasers with the centre of the imaging plane	Verify proper identification of scan plane with lasers	Daily†	± 1 mm
Orientation of gantry and external lasers with respect to the imaging plane	Test if lasers are parallel/orthogonal with scan plane over the relevant laser projection	Monthly or when daily QA tests reveal problems and after laser adjustment†	± 1 mm or 0,2° over the relevant length of the laser projection
Physical spacing between the external lasers and the gantry lasers (the scan plane)	Verify that the spacing between the external lasers and internal lasers is as pre-defined/ required	Daily or monthly and after laser adjustment †	± 1 mm
Mutual alignment of the external and internal laser systems	Verify proper alignment of the different laser systems representing the same scanning planes and verify whether they are orthogonal/parallel to one another	Monthly or when other QA tests reveal problems and after laser adjustment	± 1 mm or 0,2° over the relevant length of the laser projection
Levelness of the external and internal laser systems	Verify that the external and internal lasers are level	Annually or when other QA tests reveal problems and after laser adjustment	± 1 mm or 0,2° over the relevant length of the laser projection

Table 1b. Specifications of the quality assurance measurements for laser alignment accuracy, recommended adaptive test frequencies and corresponding tolerance limits.

* As mentioned in the text, the recommended frequencies of the tests are adaptive frequencies. I.e., it is recommended to start with the suggested frequencies and, when appropriate, the frequencies can be adapted.

† The exact frequencies used may vary among institutes, as various clinical implementations exist (depending on the clinical scan protocol - on whether or not the external laser system and a fixed spacing between the external and internal lasers are used for patient localization). Hence, the exact requirements will be institute specific.

I. CT component of PET-CT not used for radiotherapy treatment planning

In the case that a stand-alone CT is used for radiotherapy treatment planning purposes (and not the CT component of a hybrid PET-CT system), the main concern in using additional PET information is the accuracy of registration between the PET and stand-alone CT images. Hence, for this particular situation, extra quality control for a combined PET-CT system is limited. Quality control for the stand-alone CT used for planning is, however, more extensive and is part of the quality policy of the radiation oncology department.

Focussing on the co-registration of PET and planning-CT, accurate geometric and reproducible patient positioning on the PET-CT table, the planning-CT table and the radiotherapy treatment table, needs to be assured. Therefore, the PET-CT table should be flat and rigid.

For a detailed description of the associated quality controls, we refer to the next section on "Flat, rigid and level table top". For this specific clinical application (where the combined PET-CT is not used for radiotherapy planning), PET-CT table levelness is not required. When the PET-CT table is flat but not level, co-registration of the PET images with the stand-alone CT images will correct for differences in alignment that are caused by the not-level PET-CT table top. Additionally, using the same immobilisation devices as used for radiotherapy treatment will improve the accuracy of geometric and reproducible patient positioning (see paragraph 8 of the section on "Flat, rigid and level table top"). Furthermore, of importance is that the co-registration software has been validated to guarantee accurate image co-registration of PET and planning-CT images.

II. CT component of PET-CT used for radiotherapy treatment planning

FLAT, RIGID AND LEVEL TABLE TOP

1. Introduction and rationale

Hybrid PET-CT systems are often installed with a curved table top covered with a cushion that provides patient comfort. In contrast, the CT simulation scanner used for radiotherapy treatment purposes has a flat table top, just like the table used for radiotherapy treatment. When different table tops are used (curved versus flat), the patient's shape, size and location are different between the two imaging modalities. Hence, for radiotherapy purposes a flat table top should consistently be used to be able to guarantee the accuracy of co-registration.

To assure accurate geometric and reproducible patient positioning on the PET-CT table and the radiotherapy treatment table (to guarantee that a beam with a 90° gantry angle on the linear accelerator will traverse the anatomy through the same locations as imaged at 90°), both tables should be level and rigid. Additionally, it is important that the table returns to its starting position after application of pressure (that the actual table top position does not depend on the previously applied table load) and that the table fixation mechanism is rigid.

2. Frequency
It is recommended that flatness, rigidity and levelness of the table top is inspected at the time of (re)acceptance testing and whenever the system is serviced in a way that might have an impact on the table fixation accuracy, but at least once a year.
Each time the flat table top is mounted, the adequacy of its fixation should be checked.

3. Method
Table levelness should be checked with a level at different positions on the table.
As we require the table top to be level, the table will automatically satisfy the requirement of table flatness. Consequently, it is not necessary to check table flatness with a separate measurement.

Under application of loads (by exertion of pressure on the table that may be applied in different manners), it should be checked whether the table returns to its starting position after removing that specific load.
Rigidity of the table fixation mechanism should be checked by exerting pressure on the table and trying to move the table when it is mounted on the PET-CT patient handling system.

4. Required equipment
A spirit level, a phantom on which laser lines can be marked, and multiple equal weights (in total at least 75 kg) or a person of about 75 kg to mimic a patient.

5. Procedure
Table levelness
Table levelness should be checked at different locations on the table and by placing the spirit level with different orientations on the table (checking multiple directions), and with the table at different positions (relevant for scanning).

Table flatness
When from the previous procedure it can be concluded that the table is level, it can be concluded that the table is flat too. No extra measurement for flatness is then needed.

It is important to perform the measurements with substantial weight (at least 75 kg) on the table to mimic the clinical situation. Lead bricks (of equivalent heavy weights) uniformly distributed over 1,5 m length on the patient bed can be used to mimic a patient. Another possibility is to position a person of about 75 kg on the table. To analyse the impact of patient weight, the tests should be performed with and without the weights on the table. The test outcomes should always (thus with and without substantial weights on the table) satisfy the acceptance criteria (see subparagraph 7).

Returning to its starting position
To test whether the table returns to its starting position after removing a load that was placed on the table (or a manually exerted force), a phantom can be used on which the lasers are marked: (1) when no force is exerted on the table, position the phantom at the isocentre position and mark the crossing of the laser lines on the phantom. (2) Exert

a force on the table/place a weight on the table, check the new laser positions on the phantom and (3) subsequently remove the exerted force and check the laser positions on the phantom again. The force on the table top can be applied in different manners, and different table locations regarding the applied force should be considered, *e.g.* lean on both lateral sides of the table top.
This check can be performed at the position of the external and internal laser crossing at a position on the table that corresponds to the location of the patient's waist.

Table fixation - mechanism rigidity
The rigidity of the table fixation mechanism should be checked as well (to determine the play in the fixation mechanism). Check, after table fixation, whether the table can be moved (manually) by applying a small force in lateral, longitudinal and vertical directions.

6. Analysis and interpretation
Table levelness:
Check if the spirit level indicates that the table is level. If not, determine the deviation for instance by using multiple individual A4-papers: place the individual papers under one of the corners of the spirit level to create 'levelness' and check how many papers you need for this situation. You can calculate the deviation from levelness by determining the angle between the spirit level and the table.
When (assuming that the CT image matrix is aligned correctly, paragraph "CT image matrix alignment") a CT scan at a fixed table position can be used, you can check with a drawing tool in the imaging software (see notes "Table flatness") whether the table is level in the lateral direction (only at that specific position).

Table flatness:
When from the previous test it was concluded that the table is level, the table is flat too. If not, table levelness should be analysed and set correctly such that the table flatness requirement is automatically satisfied too. Important is to note that, vice versa, when the table top is not level (*e.g.* due to an inclination), it could still be flat (i.e. in case no humps are present).

Returning to its starting position:
When applying the suggested test as described in subparagraph 5, the results can be interpreted as follows: when the initially marked laser lines on the phantom deviate from the laser lines projected on the phantom after the load has been removed, the table does not return to its initial position. By measuring the difference between the marked starting position of the laser lines and the new projection of the lines, an estimation (this is just one measurement) of the deviation can be made.

Table fixation-mechanism rigidity:
If you can move the table due to application of a small force, than the table fixation mechanism is not rigid.

7. Action thresholds and actions
At (re)acceptance and after servicing of the system, factory specifications or

specifications as set by the medical physicist (based on the clinical application) must be met. If these specifications are not met, the medical physicist and/or the manufacturer should be contacted. Below, action level values are suggested (also specified in Table 1a).

Table levelness:
Suggested action levels (for both the loaded and unloaded table top):

- loaded table top, in the longitudinal direction: 10,0 mm/m (0,57°) (= 2 mm per 200 mm)
- loaded table top, in the lateral direction: 5 mm/m (0,29°) (= 2 mm per 400 mm)
- unloaded table top, in the longitudinal direction: 5,0 mm/m (0,29°, 2 mm per 400 mm)
- unloaded table top, in the lateral direction: 2,5 mm/m (0,14°, 2 mm per 800 mm)

Table flatness:
As we require the table top to be level, the table will automatically satisfy the requirement of table flatness.

Returning to its starting position:
When applying the suggested test as described in paragraph 5, the table should return to its initial starting position within ≤1mm.

8. Pitfalls and marginal notes
In principle it should be possible to use a CT scan to determine table flatness and/or levelness. However, reliable results may be hampered by humps along the longitudinal table-movement track. Performing the test with a spirit level is easier and will take less time.

For radiotherapy, the table for CT simulation is often set in a manner that without any weight on it, it has a small inclination in the longitudinal direction. This way the table remains level when the patient moves into the CT bore. This is a preventive remedy for possible table sagging that may occur when the table with patient moves into the CT bore. This might be necessary for PET-CT tables as well and will depend on the used table support.

It should be realized that in clinical practice unavoidable misalignments will occur due to patient movement, in particular due to the patient's breathing. PET images are acquired during free breathing, as the acquisition time is relatively long. CT is usually acquired during a specific stage of the breathing cycle.

For geometric precision, the same patient positioning (including immobilisation) devices as used during radiotherapy treatment, are required. To guarantee reproducibility, table markers used to specify the location of these devices, as present on the radiotherapy table top, should also be present on the PET-CT table top.
It should be noted that relatively small bore dimensions of the PET scanner can make it difficult, or even impossible, to image the patient in radiotherapy treatment position. Hence, a large PET or PET-CT bore is preferred. Furthermore, immobilisation devices

should not contain metal components that will produce CT artefacts.

Of importance is that all former tests assume no tilting of the gantry and that the gantry is fixed. However, when the gantry can be tilted, extra quality assurance tests have to be performed (those tests are described in a separately developed protocol for CT quality control. Moreover, prior to any test mentioned above, the gantry tilt should be set to zero when tilting is possible.

9. Literature

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- Paulino A.C. and The B.S., Pet-CT in radiotherapy treatment planning, Saunders Philadelphia 2008: ISBN 978-14-1-603224-3.
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TABLE SAGGING

1. Introduction and rationale

When a patient is positioned on the PET-CT table outside the bore and the table is moved in the longitudinal direction for scanning, table sagging might occur (depending on the used table translation and support system). In this way, it may happen that the table's longitudinal movement will not remain orthogonal to the scan plane and hence, the way in which the patient is imaged can be different from the way in which the patient is actually positioned on the radiotherapy treatment table. Therefore, it is of importance to verify that the absolute table sagging is small enough such that accurate geometric and reproducible patient positioning on the PET-CT table and the radiotherapy treatment table can be assured. Only in that case, the various radiotherapy beam angles used to deliver the desired radiation dose prescription will traverse the anatomy as planned on the CT scan.

2. Frequency

It is recommended that table sagging is inspected at the time of (re)acceptance testing and whenever the system is serviced in a way that might have an impact on table sagging. Additionally, an annual check is recommended.

3. Method

Table sagging should be inspected with the table at three different positions: (1) the starting position of the table outside the bore (the table position outside the bore will be used to position and align the patient with the external laser lines at the level of the

patient's waist), (2) at the scanning position with the table inside the bore (internal laser lines at the level of the patient's waist) and (3) at the scanning position with the table shifted further inside the bore (representing the most extreme case - internal laser lines at a level below the patient's waist).
These inspections should take place with a loaded and unloaded table, mimicking the effect of a patient. Lead bricks (of equivalent heavy weights) of in total at least 75 kg uniformly distributed over 1,5 m length of the patient bed can be used to simulate a patient. Another possibility is that a person of about 75 kg lies on the table while performing these measurements.

4. Required equipment

The external and internal laser systems, a laser level instrument that projects a level horizontal line or a plummet, a ruler positioned orthogonal to the table top (by fixing it to a phantom that can be placed on the table), multiple equivalent weights (in total at least 75 kg) or a person of about 75 kg to mimic a patient.

5. Procedure

As described below, table sagging is measured with the table located at three different positions. Individual measurements are performed at a position on the table that would correspond with the position of the patient's waist or with a position below the patient's waist.

Table sagging without loads

1. Position the table in its starting position. This is the table position outside the bore that will be used to position and align the patient (at the level of the patient's waist) on the external lasers. Place the phantom with the vertical ruler on the table at the position where the external lasers cross and move it 0,5 m in the longitudinal direction outwards of the bore. When the laser level is used, this instrument can be placed at the foot side of the table such that the horizontal laser line is projected on the ruler. Read and note the vertical position of the horizontally projected laser line on the ruler. Subsequently, move the phantom with the ruler over approximately 1 m in the longitudinal direction towards the bore and note the new value as marked by the laser level instrument on the vertical ruler. Recommended is to start 0,5 m before the position of the external laser crossing and end at 0,5 m after the position of the external laser crossing in the direction towards the bore. Of importance is that you note the exact value over which you moved the phantom for all these analyses.
2. Place the phantom back at the external laser crossing (reposition it at the level of the patient's waist). Move the table in the longitudinal direction until the phantom is at the position of the scan plane (where the internal lasers cross). Move the phantom over 0,5 m in the longitudinal direction outwards of the bore in the direction of the (virtual) patient's feet. Read and note the vertical position of the horizontally projected laser line of the laser level instrument on the vertical ruler. Then move the phantom with the ruler over approximately 1 m in the longitudinal direction and note the new value of the projected laser line on the ruler.
3. Place the phantom again at the position where the internal lasers cross (reposition it at the level of the patient's waist). Move the table about 0,2 m further inside the

bore and position the phantom at the position of the scan plane and move it 0,5 m in the longitudinal direction outwards of the bore (towards the patient's feet). Read and note the vertical position of the horizontally projected laser line of the laser level instrument on the ruler. Subsequently move the phantom again with the ruler over (approx) 1 m in the longitudinal direction and note the new value of the projected laser line on the ruler.

When a laser level is not available, a plummet can be used. In this case a plummet should be used with an additional fixed marker on it to be able to read the vertical location of this fixed marker on the phantom with the ruler.

Perform the same tests as specified above, but then with a person of about 75 kg on the table, or by using the lead bricks of equivalent weights, in the way specified in the subparagraph "Method".

6. Analysis and interpretation

Table sagging

Analyse the table sag at all the table positions, (1), (2) and (3). Table sagging can be determined by measuring the difference in height (Δz) of the laser level projection on the ruler, as visualized over 1 m in the longitudinal table direction (Δy,) and calculating the angle ($\tan \theta = \Delta z/\Delta y$). Figure 1 schematically displays table sagging. The vertical angle θ that the new scan plane (dotted line, representing the case with table sag) makes with the initial scan plane (solid line, scan plane without table sag) will be equal to the physical table sag (horizontal angle θ).

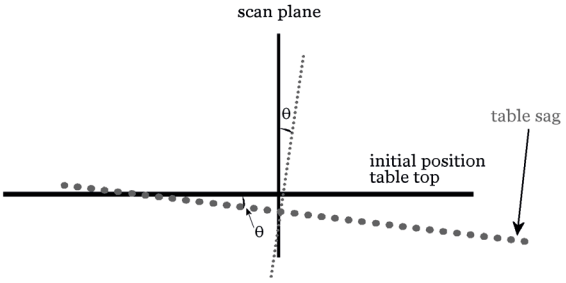

Figure 1. Schematic display of table sag. The solid lines represent the initial geometry of the table top and scan plane; the situation without table sag. The dotted lines represent the situation with table sag. The vertical angle θ that the scan plane in case of table sag makes with the initial scan plane will be equal to the physical table sag (horizontal angle θ).

When the angle deviates from zero, the table sags during the scanning of the patient and the scanning plane is tilted in reference to the longitudinal table axis. The unloaded table measurements show whether the table is installed with a small inclination in the longitudinal direction (the table would in this case rise instead of sag, see for more details paragraph 8).

7. Action thresholds and actions

On (re)acceptance and after servicing of the system, factory specifications or specifications as set by the medical physicist (based on the clinical application) must be met. If these specifications are not met, the medical physicist and/or the manufacturer should be contacted. Suggested action levels for table sag are specified below and in Table 1a.

Minimally required:

- loaded table top: 10,0 mm/m (0,57°, 2 mm per 200 mm)
- unloaded table top: 5,0 mm/m (0,29°, 2 mm per 400mm)

8. Pitfalls and marginal notes

For radiotherapy, the table for CT simulation is often set in a manner that without any weight on it, it has a small inclination in the longitudinal direction. This way the table remains level when the patient moves into the CT bore. This is a preventive remedy for possible table sagging that may occur when the table with patient moves into the CT bore. This might be necessary for PET-CT tables as well and will depend on the used table support. Hence, with regard to the previously specified measurements, it is important to pay attention to the direction in which table sagging occurs (comparing the different cases: loaded versus unloaded table).

9. Literature

- Nederlandse commissie voor stralingsdosimetrie (NCS), NCS Report 8, Kwaliteitscontrole van Medische Lineaire Versnellers – Methoden voor kwaliteitscontrole, wenselijke toleranties en frequenties, NCS, December 1995.

ACCURATE TABLE TRANSLATION

1. Introduction and rationale

To assure that the patient's position during imaging on the PET-CT corresponds to the patient's position on the treatment table, the longitudinal (in and out of the gantry) and vertical (up and down) table movement should be orthogonal and parallel to the scan plane. Remark, however, that the table movement parallel to the scan plane is not strictly required to be orthogonal. This will depend on the exact protocol used in clinical practice for scanning of the patient. Below we describe test methods with which you can verify whether the table movement is both orthogonal and parallel to the scan plane.
With the measurements specified in this paragraph, it can be assured that the table is not rotated with respect to the imaging plane and hence that the patient positioning markers can be associated with the image centre.
When the fixed spacing between the external and internal lasers is used for patient positioning or when the table's vertical and longitudinal digital indicators are used for patient isocentre marking (depending on the used protocol) the absolute table movement as displayed by digital indicators on the gantry must be accurate. Furthermore, in general, it is of importance to be able to accurately and reproducibly move the patient to any requested position in the scan field.

2. Frequency
It is recommended that accurate translation of the table is inspected at the time of (re) acceptance testing and whenever the system is serviced in a way that might have an impact on the table translation accuracy.

In the AAPM report of task group 66 it is recommended that accurate vertical and longitudinal table movement according to the digital indicators should be verified monthly, and accurate table indexing and positioning under scanner control, as displayed by the digital indicators, annually. Verification of whether the table top translations are orthogonal and parallel to the scan plane should take place monthly or when the daily laser QA tests reveal rotational problems.
Of importance is that these recommendations date from 2003 and that the currently installed systems are quite stable. The implemented frequency, with which those quality assurance tests should be performed, will depend on the specific properties of the used system, the specific clinical applications, and the requirements of each individual department. Moreover, all recommended frequencies regarding the discussed tests are adaptive frequencies (see Table 1a), i.e. it is recommended to start with the suggested frequencies and to reduce the specific frequencies when the systems are seen to be stable.

3. Method
For these tests, weights should be placed on the table to mimic the clinical situation (see also the additional note in paragraph 8). Weights of in total about 75 kg, uniformly distributed over 1,5 m length on the patient bed, or a person of about 75 kg should be used to simulate a patient.

Accurate translations orthogonal and parallel to the scan plane
Accurate orthogonal and parallel table translations with respect to the scan plane should be checked by making use of the laser projections and a phantom that is aligned with the lasers.

Accuracy of the digitally indicated table motion
Accuracy and reproducibility of the digitally indicated table motion should be tested in both the longitudinal and vertical table motion directions by making use of the laser projection. The vertical movement should be tested by using a ruler that is oriented orthogonally to the table top and moving the table up and down. The longitudinal movement should be tested by using a longitudinally oriented ruler lying flat on the table top while moving the table in and out of the gantry.

4. Required equipment
The laser system, a long ruler that can be positioned flat on the table top, a ruler that is fixed to a phantom that can be positioned orthogonally to the table top, a phantom on which laser lines can be marked, a piece of paper covering the table over the full longitudinal scan length, adhesive tape, a tape-measure, and multiple equal weights (in total at least 75 kg) or a person of about 75 kg to mimic a patient.

5. Procedure

Table translations orthogonal and parallel to the scan plane

For the table movement check two methods are suggested. Method 1 concerns a method in which you need to make CT scans with the table at two different positions and analyse those scans. With this method the movement of the table in between those two extreme positions is checked. Method 2 is much easier to perform, takes less time and is based on visual inspection only. This method assumes that the lasers are orthogonal and parallel to the scan plane (as required for CT acceptance). With method 2 the table movement along the entire track is checked.

In both cases you should mimic the clinical situation and thus use weights or, only in case no CT scans are required, a person.

Method 1

Table translation orthogonal to the scan plane:

1. Place the phantom as close to the head side of the table as possible and align it with the external lasers. Use for instance a phantom suited for laser alignment quality assurance, e.g. the Wilke phantom (Figure 3, alignment of the Wilke phantom can be performed in the way specified in the paragraph "Laser alignment accuracy"). Another phantom on which the laser lines can be marked is suitable as well. Of importance is that the phantom is aligned in the same way for the subsequent measurements. Move the table in the longitudinal direction such that the phantom is aligned with the internal lasers (without displacing the phantom itself). Make a single image through the phantom.
2. Place the phantom as close to the foot side of the table as possible and align it with the external lasers. Move the table again in the longitudinal direction such that the phantom is aligned with the internal lasers (without displacing the phantom itself). Make a single image. The location (x,y) of the phantom in this image should be identical to the location (x,y) in the first image.

Table translation parallel to the scan plane:

It should be remarked that it might not be possible to perform this check and/or that this check may not be necessary at all. For instance, when the PET-CT table moves simultaneously in the vertical and longitudinal direction while the patient is moved to the starting position of the scan. Another possibility is that PET-CT table's vertical scan position is fixed (the table's scan height is fixed). As mentioned in the "Introduction", table movement parallel to the scan plane is not strictly required to be orthogonal. The exact requirements will depend on the protocol used in clinical practice for scanning of the patient. Only when required/wished, the checks as described below may be used.

1. Align the same phantom with the internal lasers in the lowest possible scan position of the table. Make a single image.
2. Start with the previous set up. Move the table in the vertical direction to the highest possible scan position. Make a single image of the phantom. Except for the vertical coordinate, the other coordinates of the phantom in both images should be identical (use a reference point within the phantom).

Method 2:
Accurate table translation can be verified relatively quickly with visual inspection, using a phantom that is aligned with the lasers and/or by marking the laser projection over the full longitudinal scan length of the table. Use a phantom that is suited for laser alignment quality assurance, e.g. the Wilke phantom.

Table translation orthogonal to the scan plane:
Align the phantom on the external laser crossing (the lasers that indicate the coronal, sagittal and axial planes) and mark the projection of the sagittal laser on the phantom (when using the Wilke phantom with sagittal, transversal (axial) and coronal grooves of 2 mm width, use the centre of the sagittal groove for phantom alignment, see Figure 3). Move the table, with the phantom on top, in the longitudinal direction and verify whether the sagittal projected laser remains at the marked position on the phantom.
Another option for the same analysis is: draw the projection of the laser line representing the sagittal imaging plane on a piece of paper on the table top, along the entire relevant longitudinal scanning length. Move the table and check whether the laser projection stays on top of the marked line.

Table translation parallel to the scan plane:
Align the phantom on the internal laser crossing and mark the projection of the transversal laser on the phantom. When using the Wilke phantom with sagittal, transversal (axial) and coronal grooves of 2 mm width, use the centre of the transversal groove for phantom alignment, see Figure 3. Move the table in the vertical direction and verify whether the transversally projected laser remains at the marked position.
Another option for the same analysis is to draw the projection of the laser line representing the transversal imaging plane on a piece of paper on the table top, along the relevant lateral width of the table. Move the table in the vertical direction and verify whether the transversally projected laser remains on top of the marked line.

Accuracy of the digitally indicated table motion
Longitudinal motion:
1. Place a longitudinally oriented ruler flat on the table top
2. Use the internal laser projection on the ruler to determine the actual relative table translation (initial laser projection is zero table position)
3. Move the table over a range of about 20 to 50 cm in and out of the gantry
4. Note the corresponding values as displayed by the digital indicators on the gantry and the values as indicated with the laser projection on the ruler
5. Perform this measurement in total three times in the same direction of table motion and also perform it three times in the opposite direction of table motion.

Vertical motion
1. Again, of importance is to note that it might not be possible to perform this check and/or this check may not be necessary at all (see the remarks made in subparagraph 5, "Table translations orthogonal and parallel to the scan plane", "Method 1", item "Table translation parallel to the scan plane"). When required/wished, the following check can be performed: place a phantom with a ruler orthogonally on the table top. When such a phantom is not available, tape a ruler to a phantom and make sure that the angle of the

ruler with the table top is 90°.
2. Use the projected laser on the ruler to determine the actual relative table translation (initial laser projection is zero table position)
3. Move the table over a range of about 20-50 cm up and down
4. Note the corresponding values as displayed by the digital indicators on the gantry and the values as indicated by the laser projection on the ruler
5. Perform this measurement in total three times in the same direction of table motion and perform it three times in the opposite direction of table motion.

6. Analysis and interpretation

Table translations orthogonal and parallel to the scan plane

Method 1

When the longitudinal-axis and/or lateral-axis coordinates of the phantom in the two images are not identical, table translations are not orthogonal and/or parallel to the scan plane. Measure the deviation of the actual position from the required position of the reference point in the phantom by using the CT imaging software.

Method 2

Table translation orthogonal to the scan plane:

If the sagittal laser projection remains at the marked position (on the phantom or the line marked on the table) while the table is moved in the longitudinal direction over the relevant scan length, the table translation is orthogonal to the scan plane (assuming that the sagittal laser correctly indicates the plane orthogonal to the scan plane). If not, measure the deviation of the actual laser line projection from the marked laser line projection. In the latter case, the table translation is not orthogonal to the scan plane or the lasers are not accurately set orthogonal to the scan plane. When the Wilke phantom is used you can easily notice whether the laser projection stays inside the groove of 2 mm width and thus whether the deviation remains ≤2 mm.

Table translation parallel to the scan plane:

If the transversal laser line remains projected on the marked position on the phantom, the table translation is parallel to the scan plane (assuming that the transversal lasers correctly indicate the plane parallel to the scan plane). If not, measure the deviation of the actual laser line projection from the marked laser line projection. In the latter case, the table translation is not parallel to the scan plane or the lasers are not accurately set parallel to the scan plane. When the Wilke phantom is used you can easily notice whether the laser projection stays inside the groove of 2 mm width and thus whether the deviation remains ≤2 mm.

Accuracy of the digitally indicated table motion

When the travelled distance of the table as determined with the digital indicators does not agree with the distance as determined using the ruler, the digital table position indicators are not accurate.

Determine the average error and standard deviation from the measured deviations. Also check whether the deviations agree between the two opposite table motion directions.

7. Action thresholds and actions

On (re)acceptance and after servicing of the system, factory specifications or specifications as set by the medical physicist (based on the clinical application) must be met. If these specifications are not met, the medical physicist and/or the manufacturer should be contacted. Suggested action levels are specified below (also see Table 1a).

Table translations orthogonal and parallel to the scan plane

Method 1

When testing if the longitudinal motion of the table is orthogonal to the imaging plane, the reference point in the two images should be within 2 mm agreement. When using the laser lines marked on the table top, the laser projection should not deviate more than 2 mm from the marked line over the relevant scanning length and width of the table top. We do not suggest any tolerance limits for the vertical table motion direction. Of importance is to note that the orthogonal up and down table movement requirement is not always a constraint for clinical acceptance. This depends on the exact protocol used in clinical practice for scanning of the patient, hence the used tolerance limits need to be evaluated by the individual institutes.

Accuracy of the digitally indicated table motion

The longitudinal indicators should be accurate to within 2 mm. Note that the exact accuracy required depends on the way in which this table translation is used during the scan protocols. Moreover, this specific table translation has to be very accurate when this table reading is used to move the patient to the starting position of the scan (after having aligned the patient on the external crossing and having marked the reference tumour location on the patient's skin). On the other hand, it is of less importance when this table translation is not used in the scan protocols.

It is important to note that sometimes the PET-CT table top only moves in an oblique way. In that case, there is no orthogonal up and down table movement. Furthermore, in general, the exact constraints used for clinical acceptance depends on the way in which those vertical table motion readings are used in clinical practice. Hence, the used tolerance limits need to be evaluated by the individual institutes.

8. Pitfalls and marginal notes

For the longitudinal table movement check, using a ruler that is oriented flat on the table top, the table should be level and flat. In this way, the position of the laser projection on the ruler does not depend on table levelness/flatness.

For the previously specified tests, the AAPM recommends to load the table with weights (or a person) of about 75 kg to mimic the clinical situation. In this way, the influence of possible table sagging is taken into account. When the table is not loaded during these tests, the effect of measuring with a non-loaded table should be taken into account. I.e. a possible small inclination of the table top in the longitudinal direction that is a preventive remedy for potential table sagging, as previously mentioned in the chapter "Flat, rigid and level table top".

With regard to the accuracy of the digital table position indicators, the required accuracy depends on the way in which the digital indicators will be used in clinical practice.

Of importance is that all former tests assume no tilting of the gantry and that the gantry is fixed. However, when the gantry can be tilted, extra quality assurance tests have to be performed (those tests are described in a separately developed protocol for CT quality control. Moreover, prior to any test mentioned above, the gantry tilt should be set to zero when tilting is possible.

9. Literature

- American Association of Physicists in Medicine (AAPM) Task Group 66, Quality assurance for computed-tomography simulators and the computed tomography-simulation process: Report of the AAPM Radiation Therapy Committee Task Group No. 66, Medical Physics 2003;30(10):2762-92.
- American Association of Physicists in Medicine (AAPM) Task Group 2, Specification and acceptance testing of computed tomography scanners, Report of the AAPM Radiation Therapy Committee Task Group No. 2, American Association of Physicists in Medicine, New York, 1993.
- WAD protocols for quality control of radiological equipment, version 1.0, NVKF, The Netherlands, 2012.

LASER ALIGNMENT ACCURACY

1. Introduction and rationale

In radiotherapy, an external laser system is used to position the patient on both the CT table and radiotherapy treatment table. The external laser system generally consists of two horizontal wall lasers (left and right hand side) defining the coronal imaging plane, two vertical wall lasers (left and right hand side) defining the axial imaging plane, one top laser defining the axial imaging plane, and one top laser defining the sagittal imaging plane, all aligned at a fixed point outside the gantry (see Figure 2).
The general procedure is that the external lasers of the (PET-)CT scanner are used to place positioning markers on the patient's skin. Usually three markers are placed to define a single reference point inside the patient. The imaged anatomy and the position of the radiotherapy beams are related to this reference point. Hence, it is of major importance that the patient is positioned in the same way on the (PET-)CT table and the treatment table with regard to this point. Subsequently, when the patient's skin has been marked by using the external laser system, the table is moved in the longitudinal direction with a "fixed" distance such that the markers on the patient align with the imaging plane. The imaging plane is usually shown with a set of internal (gantry) lasers.

To assure accurate geometric and reproducible patient positioning on the PET-CT table and the radiotherapy treatment table, the used laser systems should be accurately aligned.

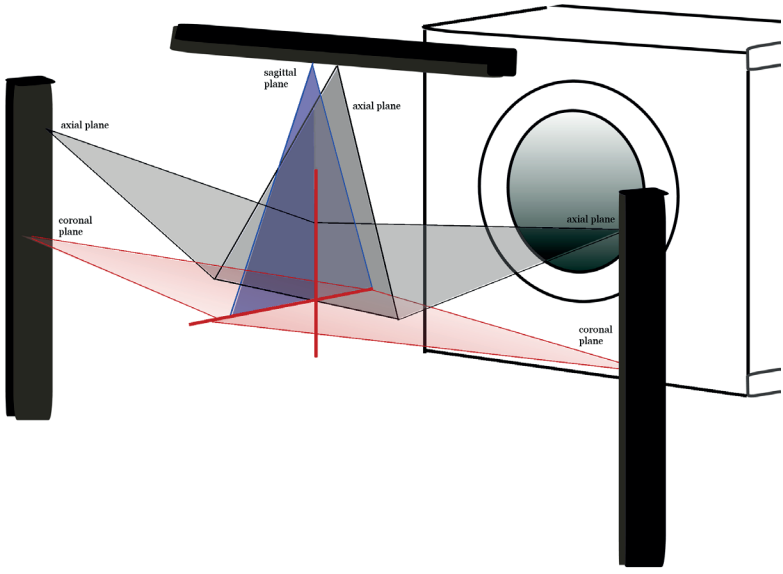

Figure 2. Schematic drawing of the CT room showing the external lasers that are used to place positioning markers on the patient's skin: two horizontal wall lasers (left and right hand side) defining the coronal imaging plane, two vertical wall lasers (left and right hand side) defining the axial imaging plane, one top laser defining the axial imaging plane and one top laser defining the sagittal imaging plane.

2. Frequency

It is recommended that the quality assurance of the laser alignment is performed at least at the time of (re)acceptance testing and whenever the system is serviced in a way that might have an impact on the laser alignment accuracy.
Furthermore, it is recommended to check the accuracy of the laser alignment with the centre of the imaging plane daily. The orientation of the external and internal lasers with respect to the imaging plane (being parallel and orthogonal with the imaging plane) and the spacing between the external and internal lasers should be checked minimally monthly. However, for the latter case, sometimes a daily check is recommended, depending on the clinical requirements and the stability of the laser setup. Moreover, the exact requirements and frequency regarding the external lasers depend on the procedure that is used to define the reference point (e.g. marking the point on the patient before or after scanning) and how the displacement between the external and internal lasers is handled (e.g. with a fixed translation or based on alignment with the individual lasers). Consequently, the exact requirements will be institute dependent.

It should be emphasized that all recommended frequencies of the tests (see Table 1b for an overview) are most efficiently considered in an adaptive protocol. I.e., it is recommended to start with the suggested frequencies and to reduce the corresponding frequencies when the systems are shown to be stable.

3. Method

For all lasers it should be verified that:
(1) they are level (in horizontal and vertical direction) with a plummet or a cross line laser level.
(2) the lasers in the corresponding planes are mutually aligned by verifying with a piece of (translucent) paper or a phantom (suited for checking mutual alignment) if the corresponding laser projections mutually coincide.

For both external and internal laser systems three other aspects should be inspected
(3) it should be verified that the external and internal laser systems accurately define the centre of the imaging plane by aligning a phantom and checking if the centre of the imaged phantom corresponds to the centre of the scanner (the centre of the imaging plane).
(4) it should be verified that the external and internal laser systems are parallel and orthogonal with the imaging plane over the relevant length of the laser projection. The same scan as made in (3) can be used: align a phantom with the laser system and check if the scanned axial and sagittal planes of the imaged phantom correspond with the axial and sagittal imaging planes.
(5) it should be verified that the spacing between the external lasers and internal lasers is as pre-defined/required. This can be tested by marking the external and internal laser projections on a large piece of paper that is fixed on the table top.
When it can be assumed that the table's longitudinal motion, as indicated by the digital indicators on the gantry, is accurate and that the table translation in this direction is orthogonal to the scan plane, an alternative test method is to mark the external laser position on the table and move the table in the longitudinal direction until the marked line reaches the location of the internal laser projection.

4. Required equipment

A plummet or a cross line laser level (projecting level horizontal and vertical laser lines), a phantom with markers suited to check (a) whether the laser projections are parallel and orthogonal with the imaging plane, (b) whether the laser systems accurately identify the centre of the imaging plane, and (c) whether the lasers are mutually aligned. The manufacturer who installs the laser system often provides such a phantom, e.g. the Wilke phantom. A tape measure, translucent paper and adhesive tape.

5. Procedure

(1) Laser levelness

For all lasers (Figure 2, the external wall lasers, the external top lasers and the internal gantry lasers) laser levelness should be checked with a plummet or a cross line laser. The tests should be performed within the relevant scanning range in both the horizontal (lasers representing the coronal plane) and the vertical direction (lasers representing the axial and sagittal planes).
When a cross line laser level is used, one can compare the horizontal and vertical projected laser lines of the cross line laser with the corresponding lines of the laser system (representing the coronal, axial and sagittal imaging planes). For visualization of the projected laser lines, a piece of translucent paper or a suitable phantom can be used that is moved along the relevant laser projection ranges.

When a plummet is used it should be checked whether the laser lines representing the coronal, axial and sagittal planes are orthogonal or parallel with the plummet.

(2) Mutual alignment
Mutual alignment should be checked for (a) the external wall lasers that are opposite from each other (Figure 2), (b) the external top and wall lasers that project the same imaging planes and (c) the external and internal lasers that project the same imaging planes or that should be orthogonal to each other.

a. Mark one of the projections of the vertical wall lasers representing the axial imaging plane on a paper that is fixed on the table top. Compare the marked line with the projection of the corresponding laser line coming from the opposite direction. For checking if the horizontally projected lasers (representing the coronal planes) coincide, a piece of translucent paper or a phantom suitable for checking mutual alignment can be used. Check the relevant scanning range.
b. Use the previously marked projection of the vertical wall laser (step (a)) representing the axial imaging plane, and compare the marked line with the projection of the external top laser defining the axial imaging plane.
c. Check if the sagittal top laser is orthogonal to the horizontal lasers of (i) the internal laser system and (ii) the external laser system by using a large piece of paper (fixed on the table top with adhesive tape) on which the laser projections can be marked:
   1. mark the sagittal top laser projection along the longitudinal axis of the table (draw a continuous line in the longitudinal direction, along the relevant part of the table);
   2. mark the horizontal laser projections of both the external (near the foot side of the table) and internal laser systems (near the head side of the table). Subsequently, measure the angles made between the marked laser projections. Additionally, with the marked line of the sagittal top laser, the mutual coincidence of the sagittal top laser with the sagittal internal laser can be checked too. Check whether accuracy of the alignment remains over the relevant laser projection length, i.e. in the area where the patient is positioned on the table.

Three other aspects that should be inspected for both the external and internal laser systems:
(3) Alignment of external and internal laser system with the centre of the imaging plane.
Can be checked with a phantom provided by the manufacturer that installs the laser system, e.g. the Wilke phantom.
The Wilke phantom has sagittal, transversal (axial) and coronal grooves of 2 mm width that can be used (Figure 3). Align the phantom such that the vertical laser lines (representing the axial plane) are projected in the corresponding transversal grooves and such that the horizontal wall lasers (representing the coronal plane) are projected in the corresponding coronal (horizontal) grooves and the sagittal top laser is projected in the sagittal groove (see Figure 3). Subsequently, the phantom should be moved to the imaging plane by moving the table in the longitudinal direction until the laser lines of the internal laser system are projected in the grooves of the phantom. Make a CT scan of the phantom for analysis. The CT image slice thickness should be as small as possible.
If the laser projections of the external and internal laser systems, as seen on the phantom, differ from each other, this measurement should be performed separately for

the two laser systems (align the phantom based on one of the specific laser systems) to be able to check the two laser systems separately. Alternatively, another solution is to assure proper mutual alignment of the lasers before performing this test.

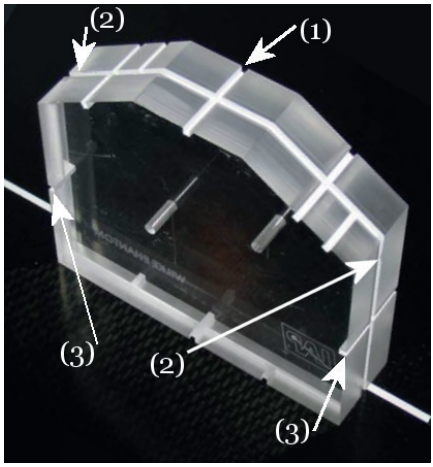

Figure 3. The Wilke phantom with its sagittal plane groove (1), transversal/axial plane grooves (2) and coronal plane grooves (3) of 2 mm width.

(4) Being parallel to and orthogonal with the imaging plane.
See item 4 of the paragraph "Method" for this procedure.
When the CT scan of the phantom is used, the CT image slice thickness should be as small as possible.

(5) Verify the spacing between the external lasers and internal lasers.
Mark the laser lines of (a) the external laser system and (b) the internal laser system on a piece of paper that is fixed to the table top. Measure the distance in between those lines (along a line that is orthogonal to both marked laser projections).
When the alternative method can be used (using the digital indicators, see the section "Method"), the differences between the indicator readings can be used to determine the absolute spacing.

6. Analysis and interpretation
(1) Laser levelness
When a plummet or a laser level instrument is used, deviation from levelness can be quantified by measuring the difference between the laser line projections of the different laser systems and the plummet orientation or the cross line laser projections (the system used as reference).
Perform these measurements along the relevant laser projection range (in the area where the patient is positioned).

(2) Mutual alignment
(a)/(b) For each pair of lasers that should be aligned, measure the distance between the

marked laser line and the projection of the corresponding laser.
(c) To verify whether the laser systems are orthogonal to each other, measure the angles between 1. the marked sagittal top laser and the marked external axial laser line and 2. the marked sagittal top laser and the marked internal axial laser line. When these angles are not 90°, the sagittal top laser is not orthogonal to the horizontal laser lines.
To check the mutual alignment of the sagittal laser projections of the external and internal laser systems, the distance between the marked external laser line and the projected internal laser line can be measured.

Three other aspects that should be inspected for both the external and internal laser systems:
(3) Alignment with the centre of the imaging plane.
Use the cross hair in the CT imaging software to determine whether the centre of the image corresponds with the centre of the imaged phantom. In case of the Wilke phantom, the centre of the phantom is defined by the crossing of the line that connects the two horizontal grooves on opposite sides of the phantom (defining the coronal plane) and the line that goes through the centre of the sagittal top groove (see Figure 3). Measure the deviation of the coordinates corresponding to this centre, from the coordinates corresponding to the centre of the image. Any deviation indicates that the alignment of the lasers with the centre of the imaging plane is not optimal.
Of importance is to note that for this test table translation in the longitudinal direction is assumed to be orthogonal to the image plane.

(4) Being parallel to and orthogonal with the imaging plane
When the CT scan of the phantom is used, the cross hair in the CT imaging software can be used. Go to the centre slice of the scan. Assuming that the Wilke phantom is used, the horizontal cross hair should be placed in the centre of the coronal grooves of the phantom (defining the coronal plane) and the vertical cross hair line should be place within the centre of the sagittal groove of the phantom (Figure 3). While scrolling back and forth through the CT slices, (a) the horizontal cross hair should accurately follow the coronal grooves of the phantom (located on both lateral sides of the phantom) and stay in the centre of these grooves. Simultaneously, in the vertical direction the cross hair should remain in the centre of the sagittal groove. With test (a) you check whether the laser systems are parallel with the imaging plane. With test (b) you check whether the laser systems are orthogonal with the imaging plane. The laser systems are not parallel and/or orthogonal with the imaging plane when the cross hair is not visualized as specified above.

(5) Verify the spacing between the external lasers and internal lasers
Compare the measured length of the spacing between the external and internal laser systems that indicate the scan plane, with the pre-defined fixed length. When the values do not agree, the spacing between the laser systems is incorrect.

7. Action thresholds and actions
On (re)acceptance and after servicing of the system, factory specifications or specifications as set by the medical physicist (based on the clinical application) must be met. If these specifications are not met, the medical physicist and/or the manufacturer should be contacted.

When the accuracy of the laser alignment with the centre of the imaging plane (daily check) or the laser orientation with respect to the imaging plane and the spacing between the external and internal lasers is not met, the medical physicist should be contacted. The suggested tolerance limits are specified in Table 1b. The older reports, like Report 11 of the Dutch Commission on Radiation Dosimetry (NCS) and the report of the AAPM Task Group 66. recommend a tolerance limit of ± 2 mm. Nowadays however, newer techniques have been introduced and the recommended a tolerance limit is ±1 mm or 0,2° (1 mm/ 290 mm). The recommended frequencies of the tests are adaptive frequencies. I.e. it is recommended to start with the suggested frequencies and reduce the corresponding frequencies when the systems are shown to be. This will also depend on the clinical protocols used.
Often, as an additional quick check, laser projections are compared with reference markers on the floor and walls. Any deviation indicates that the initial settings have been changed.

8. Pitfalls and marginal notes

When table translations are used to perform the above-mentioned tests, it should be verified that the table translation in the vertical and longitudinal direction are respectively parallel and orthogonal to the scan plane. In this way you can exclude the effect of an inaccurate table translation on the laser alignment accuracy checks.

In clinical practice the lasers can be used in different ways, e.g.:

1. The patient is positioned with the external laser system and positioning markers are placed on the patient skin based on this laser system. The table is subsequently moved by the fixed pre-defined distance between the external and internal laser systems to the scanning plane. There the alignment of the internal lasers with the positioning markers placed on the patient is only quickly checked.
2. The patient is positioned on the table at the location of the external lasers, but the positioning markers are placed on the patient's skin when the patient is aligned with the internal lasers.

The differences between the examples specified above indicate that there may be a difference with regard to the required accuracies of the laser alignment, depending on the clinical practice and requirements.

The design of the PET-CT room may also be of influence on the chosen QA protocol. For instance, in case the external laser system exists of lateral wall lasers that are not mounted in the wall but are freestanding structures, there is a chance that e.g. personnel bumps into the free standing laser system. In such a case a daily check of the laser alignment accuracy is recommended.

9. Literature

- American Association of Physicists in Medicine (AAPM) Task Group 66, Quality assurance for computed-tomography simulators and the computed tomography-simulation process: Report of the AAPM Radiation Therapy Committee Task Group No. 66, Medical Physics 2003;30(10):2762-92.
- American Association of Physicists in Medicine (AAPM) Task Group 2, Specification and acceptance

testing of computed tomography scanners, Report of the AAPM Radiation Therapy Committee Task Group No. 2, American Association of Physicists in Medicine, New York, 1993.
- Nederlandse commissie voor stralingsdosimetrie (NCS), NCS Report 11, Quality control (QC) of simulators and CT scanners and some basic QC methods for treatment planning systems – current practice and minimum requirements, NCS, September 1997.

CT IMAGE MATRIX ALIGNMENT

1.Introduction and rationale
When a PET-CT scan is used for radiotherapy purposes it is of importance that the CT image matrix is aligned correctly, i.e. not being rotated, such that the patient's position as displayed on the PET-CT image is identical to the patient as positioned on the treatment table of the linear accelerator.

The procedure to verify correct alignment of the CT image matrix is described below.

2. Frequency
The calibration should be performed at the time of (re)acceptance testing and whenever the system is serviced in a way that might have an impact on the CT image matrix alignment. Recommended is to verify CT image matrix alignment annually.

3. Method
CT scans of a phantom that includes water (displaying a clearly visible water surface in the CT image) should be acquired to analyse CT image matrix alignment.

4. Required equipment
A phantom filled with water, displaying a clear water surface when positioned on the PET-CT table.

5. Procedure
Place the water phantom in the image centre, wait till the water surface is not moving anymore and make a CT scan at a fixed table scan position. Reconstruct the CT image using the largest possible matrix.

6. Analysis and interpretation
Use the cross hair in the CT imaging software to determine the size of the margins between the cross hair line and the imaged water surface. Use the axial view of the scan that represents the image centre. The CT image matrix is aligned properly when the water surface is displayed horizontally in the image (Figure 4). Hence, when the water surface is parallel to the cross hair line, the CT image matrix is aligned properly. Margins should be measured in the axial view of the CT image.

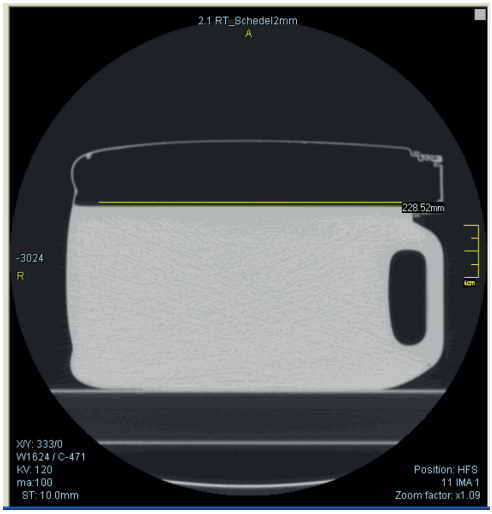

Figure 4. Example of a CT image of a tank filled with water, displaying a clear water surface. In this case the CT image matrix is properly aligned, as the water surface is parallel to the yellow horizontal line drawn with the CT imaging software.

7. Action thresholds and actions

On (re)acceptance and after servicing of the system, factory specifications or specifications as set by the medical physicist must be met. If these specifications are not met, the medical physicist and/or the manufacturer should be contacted. The suggested tolerance limit is 0,1°.

8. Pitfalls and marginal notes

In addition to a correct CT matrix alignment, proper mutual alignment of the PET and CT gantries and the corresponding images is of importance (see chapter "Co-registration in hybrid imaging devices" for more details).

Of importance is that the former test assumes no tilting of the gantry and that the gantry is fixed. However, when the gantry can be tilted, extra quality assurance tests have to be performed (those tests are described in a separately developed protocol for CT quality control. Moreover, prior to the test mentioned above, the gantry tilt should be set to zero when tilting is possible.

9. Literature

- WAD protocols for quality control of radiological equipment, version 1.0, NVKF, The Netherlands, 2012.

CONVERSION OF CT HOUNSFIELD VALUES TO ELECTRON DENSITY

1. Introduction and rationale

For dose distribution calculations in radiotherapy treatment planning, knowledge of the patient's anatomy and of the attenuation properties of the tissues is needed. To be able to accurately calculate the dose distributions for photon based treatments, tissue inhomogeneity correction should be applied, making it necessary to perform a calibration to establish the relationship between CT Hounsfield Units (HU) and the corresponding tissue electron densities. More specifically, this relationship is the basic input for radiotherapy planning systems that take tissue inhomogeneities into account for dose calculations.

It is important to note that the HU value is defined by the attenuation properties of the traversed materials and does not only depend on the tissue type itself, but also on the CT scanner (beam) properties. Hence, the HU value of a specific material may differ over time and when (as in clinical practice) different CT acquisition parameters are used. This may lead to dose calculation errors when a standard relationship between CT HU and electron densities (stored in the treatment planning system) is used for heterogeneity correction in the dose calculations.

In this chapter the procedure to calibrate CT HU to electron densities is described. Additionally, a suggestion is made how to perform the QA analyses that validates whether the calibrated relationship between CT HU and electron densities is still valid when other HUs are measured at another time point.

2. Frequency

The calibration should be performed at the time of (re)acceptance testing and whenever the CT detector is re-calibrated or replaced. Furthermore, it is recommended to annually verify the CT number conversion relationship as found during initial commissioning.

3. Method

A tissue characterization phantom should be scanned to establish the relationship between the electron density of various tissues and their corresponding CT number in HU. The found relationship has to be entered in the treatment planning system (TPS) to enable corrections for tissue heterogeneities.

4. Required equipment

A tissue characterization phantom, such as the Gammex RMI phantom, consisting of a solid water disk approximating the size of an average pelvis. Such a phantom contains various interchangeable rods with different materials of known compositions (e.g. the Gammex RMI phantom has sixteen 28 mm diameter holes in the disk that hold interchangeable rods of various tissue and water substitutes).

5. Procedure

1. Place the phantom (standing on its side) in the gantry. Position the phantom by aligning the cross hair decals with the lasers such that the lasers pass through the centre of the phantom.

2. Make a CT scan through the centre of the phantom. Appropriate scanning parameters must be chosen to minimize the effect of kV and slice thickness on the CT-to-density conversion curve. Moreover, typical clinical scan protocols as used for radiotherapy patients should be used. When different kV values are used in the scan protocols in clinical practice, separate scans and CT-to-density plots should be made for the different kV settings to be able to analyse the influence of these different settings.
3. Use a 10 mm diameter region of interest (choose dimensions that suit the used phantom), measure and record the HU for each rod. Of importance is that the central portion of each insert is considered to determine the mean CT value and its standard deviation.
4. Plot HU versus electron density for each of the rods, using the specified electron density for each rod.
   The measured data points, or a fit through the measured data points (consisting of three linear parts: a part in the lower HU range, a region of inflection and a part in the upper HU range) can be used to define the CT to density relationship.
5. Enter the resulting calibration data into the TPS.

6. Analysis and interpretation

The result of the calibration is a relationship between electron density and HU, which is needed as input for radiotherapy planning. The usual form of the calibration is a piece-wise linear relationship between relative electron density and CT units. The separation between soft tissue (air-water mix) and bonelike tissue (water-bone mix), the inflection region, is around 0-100 HU.

As a first comparison, the measured HUs can be compared with the phantom manufacturer specifications. When a second measurement is performed, verification of the calibrated CT to density conversion relationship (at the time of commissioning of the PET-CT scanner) can be performed by using a reference value: (1) the initially measured HUs (from the CT-scanner or from the radiotherapy TPS) or (2) the HUs as specified by the manufacturer.

In general, reproducibility of the calibrated curve must be ensured. Hence air should always give a HU around -1000 and water always a value around zero. In literature, some specific HU tolerance levels are suggested. The IAE report (assuming a similar determination of the HU to electron density calibration as specified in our procedure above) suggests that agreement within 0,02 for relative electron density deviations is acceptable. The Swiss Society of Radiobiology and Medical Physics (SGSMP) recommends tolerance values of ±0,05 when the electron density, normalized to that of water, ϱ_e, is less than 1,5 (e.g. for water and lung tissues) and ±0,1 when ϱ_e>1,5 (e.g. bone and more dense materials) . When using those electron density tolerances, the calibrated CT HU to electron density curve can be used to estimate the corresponding deviation in HUs.

In contrast to the previously discussed reports, not specifying anything regarding the expected errors in dose calculation, the study of Kilby et al. does relate the electron density tolerance levels to the expected dose calculation errors. Their study results are based on TPS calculations. Using maximum tissue thicknesses of 20 cm for water, 10

cm for lung and 7 cm for bone, suggested electron density tolerance levels for 6MV photon energy, and allowing a maximum dose error of 2%, are ±0,03, ±0,05 and ±0,08 respectively. Also in this case the calibrated CT HU to electron density as stored in the TPS curve should be used to estimate the corresponding deviations in HUs.

Below, a pragmatic method is described which enables you to estimate the allowed HU range based on a self set dose calculation error tolerance limit and the initially CT HU to electron density calibration stored in your TPS. In this analysis we use the tissue maximum ratio (TMR). The TMR equals the ratio of the dose at a given point in a phantom to the dose at the same point (same source surface distance) at the reference depth of maximum dose. This value does not depend on the source surface distance and only depends on the field size and the overlying tissue. Similar to other studies for estimation of the difference in dose caused by the difference in amount of density heterogeneity traversed, the gradient of TMR relative to the local TMR is used. As reference TMR data, data measured in water of a 6 MV beam for a 10x10 cm field at 10 cm depth is used, resulting in a change of TMR of 3,7% cm^{-1}.
Thomas S.J. specified the following path length values as being typical path lengths through inhomogeneities in the human body encountered in radiotherapy treatment planning: 8 cm for lung, 4 cm for fat, 8 cm for liver, 1 cm for rib, 2,5 cm for humerus and 1,5 cm for cranium. By assuming extreme path lengths through inhomogeneities one is able to make estimates for worst case scenarios. All specified parameters can be used to estimate the error in dose calculation with the following equation:

$$\Delta HU \times \frac{d\rho_{e,tissue}}{dHU} \times l \times \rho_{e,tissue} \times {}^{dTMR}\!/_{dx} \leq \Delta D_{max} \qquad (1)$$

in which ΔD_{max} is the maximum dose error caused by the variation in HU (ΔHU) of the specific tissue type (this value can be set by the user, *e.g.* a 1% dose error), $\rho_{e,\,tissue}$ is the electron density of the tissue relative to water, the ratio $(d\rho_{e,\,tissue}/dHU)$ is the derivative of the electron density curve stored in the TPS, l is the typical or extreme length traversed through the tissue and hence $l \times \rho_{e,\,tissue}$ is the corresponding water equivalent length, *dTMR/dx* is the percentage change in TMR per cm of depth (equal to 3,7% cm^{-1} as assumed and specified previously).

Hence:

$$\Delta HU \leq \frac{\Delta D_{max}}{\frac{d\rho_{e,tissue}}{dHU} \times l \times \rho_{e,tissue} \times {}^{dTMR}\!/_{dx}} \qquad (2)$$

With equation (2), the known HU to electron density calibration curve, a set value for *dTMR/dx* and a set value for $\Delta Dmax$, one can investigate whether the measured variation

in HU exceeds the allowed limit in dose error.
Below (Figure 5 and Table 2), an example of a calibration CT HU to electron density calibration curve is discussed to illustrate in what way you can use equation (2). Table 2 specifies the corresponding parameter values and estimated HU ranges that satisfy the set dose error tolerance limit, $\Delta Dmax$.
Values of the electron density, $\rho_{e,\,tissue}$, are taken from the Gammex RMI tissue characterization phantom. The allowed range in HU is determined by assuming the following linear fits to the lower HU en the upper HU part of the calibration curve (Figure 5): $\rho_e = HU/1000+1$ (for HU<100) and $\rho_e = HU/1310+1$ (for HU>200). Another option is to use the interpolated curve through the originally measured HU data points and to determine the derivative per specific point, representing a specific tissue type. However, as the first derivative may be discontinuous, it is suggested to use the mean derivative of the lower and upper part of the calibration curve in the area of that specific point.

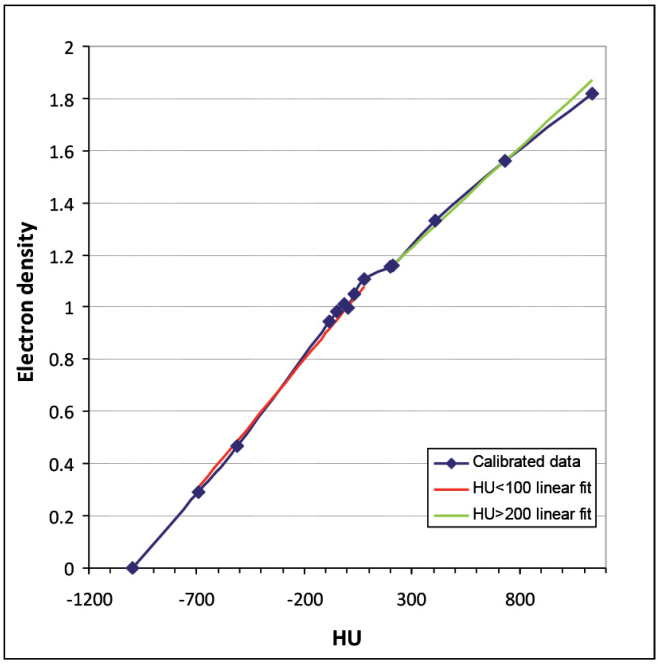

Figure 5. Example of a specific HU to relativeelectron density calibration curve. This curve is based on measurements performed with a Gammex RMI tissue characterization phantom. For this specific example, two linear fits are shown: $\rho_e = HU/1000+1$ (for HU<100) and $\rho_e = HU/1310+1$ (for HU>200).

Tissue type	Calibrated *HU*	l_t [cm]	$l_{extreme}$ [cm]	$\rho_{e,\,tissue}$	$l_t \times \rho_{e,tissue}$ [cm]	$l_{extreme} \times \rho_{e,,tissue}$ [cm]	$\frac{d\rho_{e,tissue}}{dHU}$	*dTMR/dx* [% /cm]	ΔD_{max} [%]	*ΔHU typical*	*ΔHU extreme*
Lung	-689	8	20	0.283	2.26	5.66	1/1000	3.7	1	119	48
Fat	-84	4	20	0.947	3.79	18.94	1/1000	3.7	1	71	14
Liver	78	8	20	1.077	8.62	21.54	1/1310	3.7	1	41	16
Bone	734	1.5	7	1.47	2.21	10.29	1/1310	3.7	1	161	34

Table 2. Illustration of the way in which equation (2) can be used to estimate the HU tolerance level per specific tissue type. l_t is the typical path length through the specific tissue type and $l_{extreme}$ is the extreme path length through the specific tissue type representing the worst case scenario; ϱe, tissue is the relative electron density of the tissue relative to water, $l \times \rho_{e,\,tissue}$ is the corresponding water equivalent length,; $\rho_{e,\,tissue}/dHU$ is the derivative of the HU to electron density curve (in this case determined by using the linear fits); *dTMR/dx* is the percentage change in TMR per cm of depth; ΔD_{max} is the set dose error limit; ΔHU *typical* is the estimated HU range assuming the typical path lengths encountered in treatment planning according to ΔHU *extreme* is the estimated HU range assuming the worst case scenario regarding an extreme path length per tissue type.

Advised is to use the extreme values as a first indication of the tolerance values for the measured HUs. The exact value will depend on the used value for ΔD_{max}. The estimated HU ranges are based on a simplification of the actual treatment plan and the assumption that in a specific case only the HU of one specific tissue type has been changed. However, in real patient treatments, in addition to the HU of bone, the HU of other tissues might have been changed as well. Furthermore, treatment plans nowadays often exist of beams coming from multiple directions with in-beam intensity modulation to be able to spare organs at risk. Hence, the actual dose errors may be smaller and will depend on the patient anatomy, atomic composition and exact thickness of encountered tissues per beam, and on the specific tissue transitions that are encountered. I.e. some beams will traverse many inhomogeneities, while others only traverse water-like tissue without any inhomogeneities.

7. Action thresholds and actions

Any deviation larger than the tolerance ΔHU should be closely investigated since it may reflect a technical problem or malfunction. Additionally, when the annual verification measurement shows that the CT values substantially deviate from the previously found values or from the phantom manufacturer specifications, even within the tolerance limits, the medical physicist and/or the manufacturer should be contacted.

Deviations can occur due to measurement errors, changes in the scan parameters, changes in the phantom, or the CT device may need recalibration or maintenance. If the deviations are reproducible and enduring, the CT HU to electron density table of the TPS must be adapted accordingly.

In summary, the tolerance levels as specified in literature can be used (see subsection 6 above) or the tolerance range of HUs can be determined with equation (2). In any case, the exact action level that will be most suitable depends on many items as specified above and hence should be institute specific. Moreover, taking into account typical patient anatomy, i.e. density inhomogeneities found in the patient and their typical occurrence, it

is advised to use more strict requirements regarding HU variations for tissues being more common to traverse in the human body.

8. Pitfalls and marginal notes

The position of a rod may have an effect on the rod's CT number. This is caused in part by changes in the effective energy of the beam as it passes through the phantom's solid water disk and the other rods. One can obtain a position-based correction factor by measuring the change in HU of a water equivalent rod as a function of the distance to the centre of the phantom. Often, the tissue characterization phantom already contains multiple elements of solid water that are distributed over the phantom area.

It is important that the arrangement of the different tissue elements in the used characterization phantom is the same for all performed calibrations.

Furthermore, it is important to realize that the slope of the straight portions of the graph (density versus HU), as well as the point of inflection, change from scanner to scanner (depending on, e.g., the tube voltage peak and reconstruction algorithm). Hence, calibration results should not be exchanged among scanners (even if they are from the same manufacturer).

When analysing the CT to density relationships found for different kV values, one can often conclude that the influence of using different kV settings is marginal. In general the CT number conversion relationship as found for 120 kV is often used as reference setting, as most CT scans (used clinical protocols) are made with this kV value.

In addition to the test specified above, other additional tests relevant for CT image quality control, e.g. CT number uniformity verification, CT noise analysis and accuracy of distance measurements, are of importance.

9. Literature

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Quick Quality Control

When unanticipated inaccuracies are perceived in relation to the positioning of the patient, a quick quality control can be performed. Below quality checks are described with which you can check:
- correspondence between laser orientations and scanned planes
- correspondence between the lasers and the centre of the image
- accurate table translation from the external laser crossing to the internal laser crossing

Accurate table translation/laser alignment accuracy
Accurate table translation can be verified quickly with visual inspection, using a phantom that is aligned with the lasers.

Use a phantom that is suited for laser alignment quality assurance (e.g. the Wilke phantom, Figure 3):
1. Align the phantom at a marked position on the external lasers (the lasers that indicate the coronal, sagittal and axial planes).
2. Move the table in longitudinal direction and verify whether the coronal projected laser remains at the marked position.
3. Move the table in vertical direction and verify whether the transversal projected laser remains at the marked position.

A deviation may have different causes like an inaccurate laser alignment or a non-accurate table translation and should be further investigated. When the required accuracy is not met, the medical physicist should be contacted.
It should be remarked that it might not be possible to perform this check and hence this check may not be necessary. E.g. when the PET-CT table simultaneously moves in the vertical and longitudinal direction while the patient is moved to the starting position of the scan.

Accurate indication of the centre of the image
Additionally, it can be quickly verified whether the laser systems correctly indicate the centre of the image, whether the distance in between the external and internal laser systems is as pre-defined, and whether the table movement is orthogonal to the scan plane. This can be done by using a phantom suited for laser alignment quality assurance (e.g. the Wilke phantom, Figure 3):
1. Align the phantom on the external laser system.
2. Move the table in longitudinal direction such that the phantom is aligned with the internal lasers.
   In this way you check: the pre-defined fixed distance between the two laser

systems, whether the longitudinal table movement in between those two points is orthogonal to the scan plane and whether the two laser systems are properly aligned.

3. Scan the phantom with the smallest CT slice thickness.
4. Use the cross hair in the CT imaging software to determine whether the centre of the image corresponds to the centre of the imaged phantom. In case of the Wilke phantom, the centre of the phantom is defined by the crossing of the line that connects the two horizontal grooves on opposite sides of the phantom (defining the coronal plane) and the line that goes through the centre of the sagittal top groove. Measure the deviation of the coordinates corresponding to this centre, from the coordinates corresponding to the centre of the image.
5. By going through several slices and looking at the left and right ditches and front and back sides of the phantom you can see if the phantom is in alignment with the scan plane.

Any deviation may indicate that the alignment of the lasers with the centre of the imaging plane is not optimal or that the mutual alignment of the two laser systems is not satisfactory or that the table movement is not orthogonal to the scan plane. When specifications are not met, the medical physicist should be contacted.
It is recommended to check the accuracy of the laser alignment with the centre of the imaging daily (see the section "Laser alignment accuracy"). As the above-specified checks can be performed rather quickly, one could choose to add these extra measurements to the daily check. However, the actual clinical implementation of the specified quality controls will depend on the clinical application of the PET-CT. Hence, to determine which measurements will be relevant to include in the daily check should be discussed with the medical physicist.

PET-CT Co-Registration

Routinely checking the accuracy of the image co-registration in a hybrid PET-CT system is of importance for multiple reasons. Errors in registration will cause inaccuracies in attenuation correction procedures and improper correlations of anatomy and function. In particular, when combined PET-CT is used for radiotherapy applications, including radiotherapy treatment planning, the accuracy of image registration becomes even more important.

For quality control of co-registration in PET-CT, we refer to the chapter "Co-registration in hybrid imaging devices". The used testing frequency and action levels will depend on the specific clinical application and should be determined in collaboration with the medical physicist.