



Original paper

EFOMP's protocol quality controls in PET/CT and PET/MR

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A B S T R A C T

This article presents the protocol on Quality Controls in PET/CT and PET/MRI published online in May 2022 by the European Federation of Organisations for Medical Physics (EFOMP), which was developed by the Working group for PET/CT and PET/MRI Quality Control (QC) protocol.

The main objective of this protocol was to comprehensively provide simple and practical procedures that may be integrated into clinical practice to identify changes in the PET/CT/MRI system's performance and avoid short- and long-term quality deterioration.

The protocol describes the quality control procedures on radionuclide calibrators, weighing scales, PET, CT and MRI systems using selected and measurable parameters that are directly linked to clinical images quality. It helps to detect problems before they can impact clinical studies in terms of safety, image quality, quantification accuracy and patient radiation dose.

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<https://doi.org/10.1016/j.ejmp.2022.11.010>

Received 29 June 2022; Received in revised form 25 November 2022; Accepted 26 November 2022

Available online 18 December 2022

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CT and MRI QCs are described only in the context of their use for PET (attenuation correction and anatomical localization) imaging.

Detailed step-by-step instructions have been provided, limiting any misinterpretations or interpersonal variations as much as possible.

This paper presents the main characteristics of the protocol illustrated together with a brief summary of the content of each chapter.

A regular QC based on the proposed protocol would guarantee that PET/CT and PET/MRI systems operate under optimal conditions, resulting in the best performance for routine clinical tasks.

Introduction

Since the first generation of PET systems, a dramatic improvement in both hardware and software has been observed. In the last years, the Time of Flight (TOF) technology coupled to high light output lutetium-based scintillators and the newest silicon photomultipliers development led to a widespread commercial introduction of digital TOF-PET systems, even in the whole-body configuration [1]. The continuous advancements in PET technology, improvement of the TOF resolution, increased effective sensitivity, and better count rate performance translate into a superior image quality and lesion quantification accuracy in PET whole body imaging.

PET imaging involves several steps: radiotracer production and administration, PET data acquisition, data corrections (randoms, scatter, attenuation, normalisation) and image reconstruction which can be performed with different algorithms and settings. The complexity of PET imaging requires a clear quality control (QC) procedure at different levels, from tracer production up to the final image formation and interpretation.

Along with PET imaging itself, computed tomography (CT) and magnetic resonance imaging (MRI) are mainly used for attenuation correction and anatomical localization.

Guidelines for QC of PET systems have already been proposed by professional bodies such as the International Atomic Energy Agency [2,3], the American Association of Physicists in Medicine [4], the Institute of Physics and Engineering in Medicine [5] and the European Association of Nuclear Medicine [6]. PET acceptance tests have been extensively described by the National Electrical Manufacturers Association (NEMA) [7] and the International Electrotechnical Commission (IEC) [8] standards.

Most of this literature on routine quality control (QC) in PET/CT systems is out-of-date or no longer relevant, particularly with respect to the latest generation of digital and long axial field-of-view (LAFOV) PET/CT systems. The scenario for PET/MR QC is also confounded, because of the lack of dedicated QC recommendations from professional working bodies for these hybrid systems.

The EFOMP working group (WG) on QC in PET/CT and PET/MR was issued to propose a guideline on a routine quality control schedule to be performed on digital and non-digital systems. The aim was to identify a set of QC tests that will be simple and straightforward to perform without the need for special phantoms or equipment and sophisticated software for image analysis.

A survey on QC in PET/CT and PET/MR was sent to a large community of medical physicists across Europe in June 2020, with the intention to collect information on the different practices, opinions and relevance of the QC tests, as well as the availability of different phantoms [9]. The results of the survey show that there is a lack of harmonization in the PET QC procedures across Europe, in terms of tests and phantoms used, also outlining a great variability in the tests related to PET quantification and in the number of PET systems accredited by national or international organizations. A great variability was also reported for the type and age of the PET systems installed, requiring consideration for practical measure setup. This information guided the WG in tailoring the set of quality control measures as part of this guideline.

This paper is a summary report of the EFOMP Guideline on QC on PET/CT and PET/MRI [10] that presents the essential tests to ensure the

operational status of the PET devices. The protocol was written considering PET systems with an axial field (AFOV) of view below 30 cm, but all the tests can be extended to LAFOV systems. Thus, any test specific to such LAFOV devices is not presented in the current guideline.

The protocol describes the quality control procedures of radionuclide calibrators, weighing scales, PET, CT and MRI systems using selected and measurable parameters directly linked to clinical images quality. It helps to detect problems before they can impair clinical studies in terms of safety, image quality, quantification accuracy and patient radiation dose. CT and MRI QC are described only in the context of their use for PET (attenuation correction and anatomical localization) imaging.

A regular QC based on the proposed protocol would guarantee that PET/CT and PET/MRI systems operate under optimal conditions, resulting in the best possible performance in routine clinical tasks, respectively.

Protocol characteristics

Rationale of the QC protocol

A quality assurance program should start with an *acceptance test*, which is intended to verify that the system is operating according to manufacturer's specifications. The acceptance test is performed following the vendor's specification based on international standards before the system is handed over. It provides uniform and consistent methodology for measuring and reporting the specific performance parameters of an imaging system. The international standards of reference are published by the NEMA and the IEC and are regularly reviewed and updated to include technological innovations of the equipment.

The acceptance test should be performed immediately after the installation and prior to clinical use. Acquisition and evaluation of the result is often available only under service system access and not for the regular user.

After acceptance, a QC programme is specifically required to test the constancy of the performance of the equipment throughout its lifetime. Its content may differ from that defined from the international standards of reference. All acquisitions and evaluations must be available to a regular user.

The QC protocol should describe the tests to perform and their periodicity: the results obtained during a first few executions after acceptance will establish baseline reference and tolerance data for comparing all future QC results. Thereafter, performance testing is conducted on a regular basis (*constancy tests*) and whenever any maintenance procedures potentially affecting the performance of the system (*status test*) occurred.

The QC program defined in such a way will allow to detect and correct short- and long-term deteriorations in quality.

The aim of a QC program is to detect changes in the performance of the PET/CT/MRI system using measurable parameters directly linked to the quality of clinical images. In other words, it helps to detect problems before they can impact the validity of clinical studies in terms of safety, image quality, quantification accuracy and radiation dose to patients and staff. An effective QC program should include tests that shall be simple, practical and compatible with the clinical routine.

Key point of the QC protocol

The key points of a QC protocol include the definition of:

- **Type of tests:** they must be identified following phantom availability, guidelines, national legislation, type of the equipment and clinical use of the imaging system (i.e. use of PET images for radiotherapy purposes, hybrid system).
- **Frequency of tests:** it should be defined considering a compromise between accuracy and feasibility of tests.
- **Tolerances:** they should be established with the guidance of both from manufacturer recommendations and international guidelines.
- **Corrective actions:** when a QC exceeds the established tolerance, it is essential to clearly define the actions that must be taken (i.e.: repeat the QC, schedule a corrective maintenance, limit the clinical use of the system).
- **Responsibilities:** the Medical Physics Expert (MPE) is responsible for the overall supervision of the QC program, including supervision of tests performed by other professionals (e.g. technologists).
- **Recording:** record keeping is a necessary part of a QC program. Detailed local operating procedures and instructions should also be written, as part of the quality assurance program. The periodic analysis of the tested parameters' trend is fundamental to properly monitor the system performance and to promptly identify possible faults.

All the results and the images of all the QC performed should be recorded and archived with care. For the same test, the results should be compared with those of the initial QC (performed as part of or after the acceptance test) and trends over time should be analysed.

Each MPE is free to carry out additional QC, to increase the frequency of QC or to decrease the tolerances to adapt to his own clinical configuration and to national regulations.

In the event of out-of-tolerance results for one of the tests, it is suggested to follow the national recommendations and inform the device manufacturer. Type and timing for corrective actions should be defined locally by the MPE and the nuclear medicine physician according to the clinical relevance of the problem.

Phantoms

PET phantoms

All manufacturers use sealed sources of different shapes and radioisotopes for PET daily quality control. These sealed sources must be renewed regularly to ensure the minimum activity recommended to perform the QC. All manufacturers also offer a cylindrical phantom fillable with water to calibrate and evaluate the radioactivity concentration result, SUV value and cross-calibration with the calibrator, respectively. The dimensions of such phantoms and in particular the length vary according to varying system configurations and manufacturers, respectively. These phantoms are delivered with a support allowing them to be placed in the centre of the PET field of view.

The most common phantom used for characterizing PET image quality and for accreditation programs is the IEC Image quality phantom [11] (Fig. 1). It represents a body phantom consisting of acrylic glass material with a volume of approximately 9.7 L (interior length of phantom: 180 mm). Six fillable spheres of various sizes (inner diameter: 10, 13, 17, 22, 28 and 37 mm) can be inserted into the body phantom in the same plane. An insert containing Styrofoam beads in water, intended to represent lung or a lung equivalent material, can be positioned in the centre of the phantom.

The manufacturer internal quality control procedures also propose specific phantom or sealed sources to test the superposition of the volumes of PET and CT or MR [12–18].

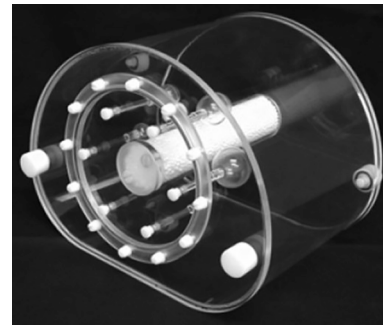


Fig. 1. IEC image quality phantom.

CT phantoms

All manufacturers provide a CT image quality phantom with their PET/CT. The phantom has a uniform section filled with water or equivalent material. The phantom also has at least one section with a minimum of 3 different materials: water and air are mandatory and at last one could be an acrylic zone. This image quality phantom could also contain other layers for different tests (resolution, slice thickness, contrast). These phantoms are delivered with a support allowing them to be placed in the centre of the CT *trans*-axial field of view. There are also PET/CT vendor-independent phantoms available for CT characterization such as the ARC and the 500–600 Catphan family (Fig. 2). The present protocol does not adopt any specific phantom, although using vendor-independent phantoms is advisable to allow inter-comparisons between centres.

MR phantoms

Phantom contents used for MRI quality tests are in the form of an aqueous solution or gelling solution (agarose) doped with paramagnetic components (e.g. copper sulphate).

The two PET/MR manufacturers used a spherical homogenous phantom for daily MR quality control. Other quality control phantoms provided by the manufacturer or proposed in a specific standard (Eurospin [19], ACR [20]) are dedicated to the measurement of a metric or different metrics such homogeneity, geometrical distortions, slice parameters, high and low contrast resolution (See Fig. 3).

Detailed descriptions of test procedures

The protocol tests are grouped in several chapters, one for each equipment. Each test is accurately described to facilitate the phantom preparation, when needed, the test execution and the image analysis.

Each test procedure of the Protocol is described along these lines:

- Purpose
- Materials
- Procedure
- Analysis
- Tolerance

Four appendixes to the protocol were added, three of them contain detailed information on specific QC procedures (routine manufacturer recommended QC on the PET component and daily QC as well as QC on the CT component and QC on the MR component). In the fourth appendix a template for reporting QC results is presented.

The list of the test included in EFOMP Protocol QC on PET/CT and PET/MRI are reported in Table 1.

Radionuclide calibrator

Any routine manufacturers QC should be performed as well as the following additional tests. Drift on the electronics system diagnostics,

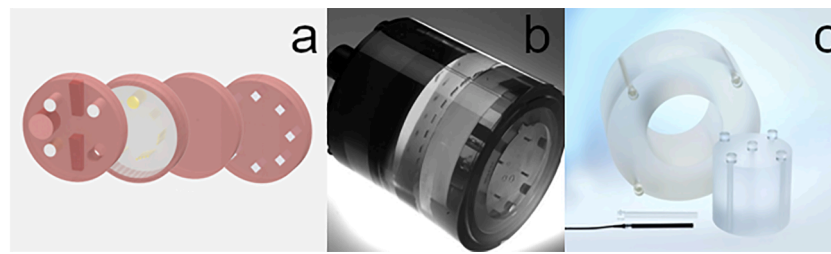


Fig. 2. ARC phantom (A), Catphan 600 (B), CTDI phantoms (C).

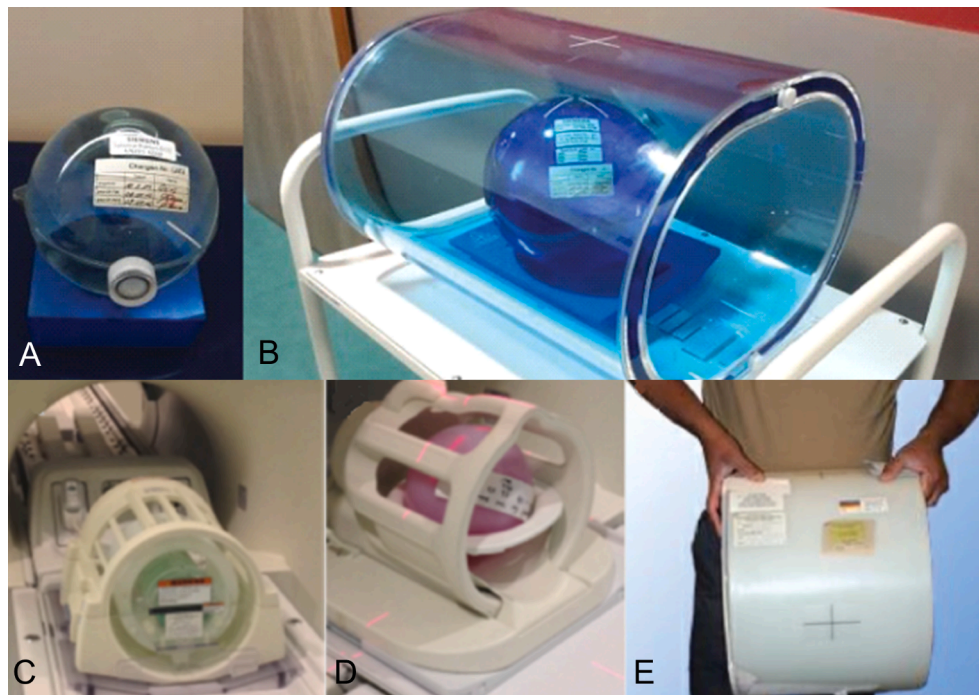


Fig. 3. Top row Phantoms for MRI Quality Control on the mMR (Siemens Healthineers) (A, B); bottom row Phantom DQA-III (A), Head phantom (B), Body phantom (C) (GE Healthcare).

the stability of the high voltage and the adjustment of the zero gain should be observed when measuring the daily check source. Correction factors for vial/syringe geometry should be eventually considered. Relevant maintenance that could affect the performance of the radionuclide calibrator are replacements of the ionization chamber, electronics, or change in HV supply. QC on the radionuclide calibrators include physical inspection, background check and a constancy test on a daily basis at least. Accuracy, precision and linearity tests should be performed on an annual basis. The inter-calibration run annually on all the radionuclide calibrators of a PET centre can guarantee the homogeneity of readings of different calibrators with a clinical isotope. For a detailed description of the QC tests on a radionuclide calibrator refer to the specific guidelines [21–23].

Weighing scales

To allow comparability between patients and different injected activity, PET uptake is normalised by the injected activity and patient weight to give units of Standardised Uptake Value (SUV). Since SUVs are based on such measures as body weight, lean body mass [24] or body surface area [25], the weighing scales used need to be accurate and precise as the accuracy of the results is decisive for the accuracy and validity of the SUV. The precise knowledge of patient's weight is also important to maintain a constant image quality through a personalized

amount of administered activity, i.e. following diagnostic reference levels of activity to be administered per kg. of body weight. Users should be aware of and follow the requirements of any country-specific regulation relating to weighing instruments in a hospital environment. The scales would have a capacity suitable for the range of patient weights to be measured and units should be displayed in metric and have scale intervals suitable for the size of patients. Factors impacting the accuracy of weighing scales are workload, age, how well they are taken care of and how often they are moved.

Weighing scales should be checked by a physical inspection (free from damage, powered by batteries, accurately levelled, zero value displayed before weighing patient, accurate weighing scale selected) and for their accuracy and precision on an annual basis, by using calibrated weights.

PET system

Traditional axial field of view (≤ 30 cm) PET systems are considered in this document. LAVOF-systems (> 30 cm) differ in sensitivity, count-rate-activity curves and spatial resolution with respect to traditional FOV ones and, thus, require measurements and phantoms specifically designed for this category of PET systems [26,27]. The quality control tests were chosen to be suitable for practical use, considering possible variations in practices based on the type of the PET/CT and PET/MRI

Table 1

List of the test of the EFOMP Protocol QC on PET/CT and PET/MRI.

Category	Test	Periodicity	Purpose
Radionuclide calibrator	Physical Inspection	Daily	To check the integrity
	Background	Daily	To verify that the background activity is within an acceptable range
	Constancy	Daily	To check the constancy and reproducibility of the calibrator measurements over time
	Clock synchronization	Monthly	
	Accuracy	Annually	To test the accuracy of the system for a series of selected known sources
	Precision	Annually	To check the short-term counting reproducibility of the system
Weighing scales	Linearity	Annually	To test that the system is linear in response over a range of dispensed activities
	Inter-calibration	Annually	To test the homogeneity of readings of different calibrators with a clinical isotope
	Physical Inspection	Daily	To check the integrity
	Accuracy and precision	Annually	To check the accuracy over a range of calibrated weights and short-term readings
PET scanner	Uniformity/artefacts	Quarterly and after RM	To check the ability of the system to depict uniform regions of a phantom with the same intensity
	SUV validation/quantification accuracy	Quarterly	To verify accuracy of SUV values
	PET/CT and PET/MR alignment	Semi-annually and after RM	To ensure proper attenuation correction and localization
	Count rate performance (*)	Annually or after RM	To verify quantitative accuracy of reconstructed activity concentration (or SUV) over a clinically relevant ranges of activities
	Image quality	Annually	To evaluate the quality of the acquired and reconstructed images using parameters for clinical imaging of the torso
CT scanner (for PET/CT)	Image artefacts	Monthly	To ensure that no artefacts that could compromise the CT functionality are present
	HU uniformity and noise	Monthly	To ensure that the CT numbers are uniform across the field of view
	HU accuracy	Annually	To verify that the CT numbers are within an appropriate interval
	Slice thickness Dose measure	Annually	To evaluate the accuracy of the CT dose index in air (CTDI _{air})
MR scanner (for PET/MR)	Uniformity of image signal	Monthly	To check the ability of the system to depict uniform regions of a phantom with the same intensity

Table 1 (continued)

Category	Test	Periodicity	Purpose
	Signal to Noise Ratio (SNR)	Monthly	To measure the SNR in all three orthogonal planes
	Attenuation map	Acceptance or after RM	To test the dedicated attenuation correction process

RM: Relevant maintenance.

(*): The linearity test to check the persistence of count rate performance is suggested only for the PET centres that perform clinical dynamic acquisitions.

systems and availability of phantoms.

Relevant maintenance tasks affecting the performance of the PET system are replacements of detectors, photomultiplier tubes (PMTs), pulse shape discrimination (PSDs), electronics and reconstruction software.

Uniformity and artefacts should be checked for quarterly and after relevant maintenance by means of a uniformly filled ^{18}F phantom or ^{68}Ge cylindrical phantom scanned with the clinical whole-body protocol. Reconstructed slices should be inspected for the presence of any non-uniformity areas (Fig. 4) [28].

SUV validation represents a fundamental test to verify accuracy of SUV values. It can be performed together with the uniformity test, provided that the ^{18}F activity is accurately measured and the assay time registered.

The count rate performance can be tested in terms of linearity of activity concentration and/or SUV values over a clinically relevant ranges of activity concentrations. This test is suggested only for the PET centres that perform clinical dynamic acquisitions, which require very high activities (i.e. with ^{82}Rb). A uniform cylinder can be scanned with the protocol routinely used for dynamic imaging and for a duration of at least 7 half-lives of the radionuclide used. The mean activity concentration in the phantom measured in the image obtained during the whole acquisition time should match the actual activity concentration in the phantom.

The image quality test proposed in the protocol is a simplified version of the image quality test described in the NEMA NU-2 standard [7]. In particular, the test uses six hot spheres and does not require the use of the scatter phantom to simulate activity outside the AFOV. Typically, ^{18}F will be used, but different isotopes should be tested in advance to their use, especially when high prompt gamma contribution is expected (i.e. with ^{124}I). If performing this test on a PET/MRI systems, special attention must be paid to the attenuation correction. Detailed information for phantom preparation is provided in the protocol. As a minimum, two acquisitions should be performed, a single static acquisition centred over the spheres using the clinical FDG protocol used over the torso for a 70 kg adult and a 2–3 bed position or continuous flow acquisition to cover the whole phantom using the clinical FDG protocol used over the torso for a 70 kg adult. To investigate different scan times, the acquisition should ideally be performed in list mode for at least 5 min per bed. Shorter scan times and frames can be rebinned from the list mode data, retrospectively. PET data should be reconstructed using the standard clinical reconstructions. The PET raw data along with the CT data used for attenuation and scatter correction should be retained to allow retrospective reconstruction if new reconstruction algorithms or corrections are provided in the future.

However, with the increase of the axial field of view, this data-sets can grow into the rage of some ten GB/data-set and the respective storage capacity must be planned for well in advance of installation and use of such systems.

The reconstructed images (Fig. 5) should be quantified in terms of *Recovery Coefficient* for the visible spheres and *Coefficient of variation of the background*. This test is suggested to be performed on an annual basis.

Finally, the PET/CT and PET/MRI alignment should be tested to ensure proper attenuation correction and localization. Point/sealed

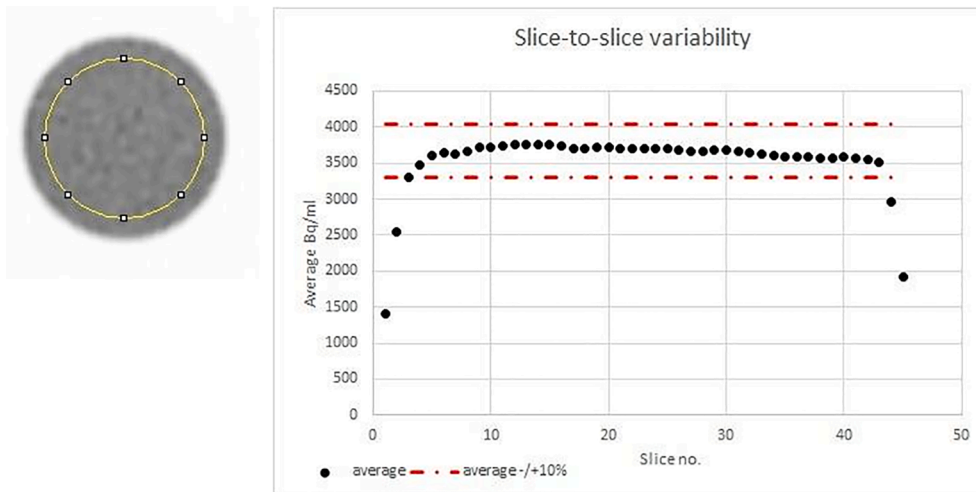


Fig. 4. Reconstructed slice of the uniform phantom for inspection for presence of any non-uniformity areas within the 80% of the axial FOV and Slice-to-slice variability in the average concentration and the limits of $\pm 10\%$ within the 80 % of the axial FOV.

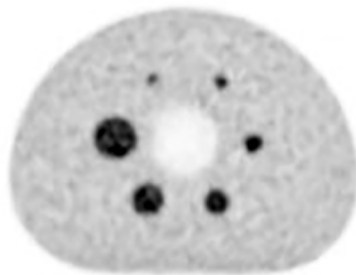


Fig. 5. IEC Image quality phantom showing hot spheres filled with ^{18}F -FDG with target-to-background ratio of 4.

sources as suggested by the manufacturer should be used and the test should be performed in accordance with the manufacturer's procedure for data collection, reconstruction and analysis. For just visual analysis, it can also be done by using a clinical protocol.

QC for PET accreditation programs

There are several PET system accreditation programs being followed in the EU, such as by EARL, UK PET Core Lab, Italian Foundation on Lymphoma or the SNMMI Clinical Trials Network. Quantitative imaging biomarkers need to be repeatable and reproducible. The latter is also important for clinical care when quantitative PET metrics are used for diagnosis, prognosis, prediction and therapy response assessment. Therefore, the main aim of these programs is to harmonise image quality and quantification across imaging sites to facilitate multicentre trials and to use quantitative PET biomarkers in clinical care.

All programs have a QC test for calibration accuracy and uniformity, e.g. based on a uniform cylindrical phantom. This test verifies correct cross-calibration between the dose calibrator and the PET/CT (or /MRI) system. In addition, and most importantly, an image quality QC is performed with a phantom containing high contrast spherical objects, such as the IEC phantom (EARL, UK PET Core Lab and Italian Foundation on Lymphoma) or an anthropomorphic phantom (by the SNMMI-CTN). Sphere to background ratio ranges from 4 up to almost 10 in order to assess partial volume effects, i.e. the level of contrast recovery in each sphere of the phantom resulting from system resolution, reconstruction settings and filters. These recovery coefficients are reported as function of sphere size and performance specification for allowable recovery coefficients are provided. Accreditation programs aiming at PET

performance harmonisation have published lower and upper limits for recovery coefficient as function of sphere size for SUVmax, SUVpeak and/or SUVmean. In several programs, the accreditation process is repeated quarterly (calibration) or annually (image quality) and ongoing (re-)accreditation is granted when the PET system and acquisition/reconstruction protocols meet the required accreditation criteria. In this way a constant and harmonized PET system performance is guaranteed.

CT system

In modern PET/CT systems, the CT part can be used exclusively for attenuation correction, as a reference for anatomical localization or as a fully diagnostic modality. From the PET perspective, the main objectives of the quality controls on the CT component are the correct alignment of both modalities and the stability of the HU (for a precise attenuation correction).

The alignment between modalities is previously assessed on the PET QC section. Refereeing the stability of the HU, the main aspects that could affect are the presence of artefacts, the instability of HU uniformity and noise, and the HU accuracy. All those parameters should be checked at least monthly. Additionally, slice thickness could compromise the attenuation correction and should be checked at least annually. To perform all these tests, most common vendor-neutral phantoms are the ARC phantom and the 500–600 Catphan, although different solutions could be found for each parameter tested. Although not directly linked to the PET functionality but, as it is a crucial parameter to be controlled in the light of the patient's radiation protection, the radiation dose measurement is included in this section. Of note, these additional tests are necessary to ensure a proper operation of a CT as described in different guidelines [29–31]. Also, if the PET/CT is used for radiotherapy planning, additional tests should also be performed, the guideline includes those procedures in an appendix.

MR system

As for CT, the QCs proposed for the MRI component does not seek to provide a complete image quality assurance program, but to test parameters that may affect PET images through the attenuation correction.

From this perspective, the uniformity and the constancy of the signal-to-noise ratio with respect to the baseline value should be checked monthly. Both tests can be performed with a homogeneous phantom. We recommend testing the most commonly clinical MR sequence and all sequences used for attenuation correction with the corresponding coil.

Other important QCs for the MR image quality evaluation are reported as an appendix.

In addition to this QC, a test of the MR-based attenuation correction process used in PET/MR is suggested. PET/MR systems use a dedicated method for patient attenuation corrections as the attenuation coefficients could only be derived from MR data [32]. The MR-based attenuation correction applied in clinical routine is based on the acquisition of dedicated MR sequences, followed by tissue segmentation. Fixed attenuation coefficients are then assigned to each segmented compartment. In addition, because the fact that the *trans*-axial field of view is smaller in MR than in PET, a correction must be applied to avoid truncation of the attenuation map for body portions that exceed the dimensions of the *trans*-axial FOV in MR (especially patient's arm). This attenuation correction method is not directly applicable for QC tests with phantom acquisitions for several reasons. The objective/signal of a MR measurement is a proton density. This is by no means related to the attenuation behaviour of a material (electron density). Thus, and due to the fact, that the composition of most of the phantoms is different from that of human tissues, the patient's tissue segmentation algorithms may not be able to properly visualize phantom components and, thus, determine their attenuation features. Moreover, pure water as usually used for phantom filling creates strong artefacts in MR images [33–36]. As a result, attenuation correction methods are not able to correct for phantom plastic walls. Due to these uncertainties, several publications [21,37] demonstrated that the MR-based attenuation correction can lead insufficient quantification results as compared to CT-based attenuation corrected phantoms measurement used in standard PET QCs. In order to obtain reliable and robust QC results, alternative and dedicated methods for phantoms' attenuation correction are needed. The most frequent solution is to use a pre-defined attenuation map obtained from a CT acquisition of phantoms provided by the manufacturer, in order to obtain attenuation coefficients of all phantom parts. The main drawback to use CT maps for the attenuation correction of the PET phantom data is that it is currently not possible to test the accuracy of the attenuation sequence used in PET/MR using phantoms. A procedure using attenuation maps of clinical patients is proposed in this protocol. The accuracy of the segmentation method used to classify different tissues and the efficacy of the truncation correction method must be tested in acceptance test or after relevant upgrades in the sequence used for attenuation correction. For each μ -map, the suggestion is to verify that the segmentation has correctly identified the expected number of compartments (soft tissue, air, lung, adipose tissue, and eventually bone) at least and has assigned the expected linear attenuation coefficient. In addition, one should verify that the peripheral regions not visible in MRI are included into the attenuation map. In the clinical routine, the attenuation map used for each patient must be visually checked in PET/MR. In the future, manufacturers should propose alternative solutions to test this issue under controlled conditions. In literature, alternative solutions with home-made phantoms are proposed, but they still remain pilot studies to be proposed in a quality control program.

QC for radiotherapy applications

Users must consider the accuracy required for delineation of normal and target volumes when defining the scope of QC requirements for radiotherapy applications. This ranges from the simplest applications where the PET is used as a visual aid for the oncologist helping to determine the extent of a tumour or involved lesions or if healthy tissues can be avoided, to the most complex applications where the CT from the PET-CT is directly used for radiotherapy treatment planning [38,39].

The key aspects for any QC programme are tests for PET to CT (or MR) alignment and integrity of the data when imported into the planning system. This ensures the PET data is displayed appropriately and can be correlated with anatomical data from CT and MR.

Where the highest levels of accuracy and precision are required for outlining the biological tumour volumes, the positioning of the patient is

critical. In this case, the PET system must be commissioned and undergo routine quality control testing in line with the guidelines for CT simulation in radiotherapy applications. These are provided in AAPM Report 83 [40].

Conclusion

EFOMP protocol QC on PET/CT and PET/MRI was aimed at detecting any changes in the performance of the PET/CT/MRI system, through the use of selected and measurable parameters directly linked to the clinical image quality.

The key point for this protocol was to devise simple, practical and clinical routine compatible QC tests without the need to have specific phantoms and sophisticated software for image analysis.

A regular QC based on the proposed protocol would guarantee that PET/CT and PET/MRI systems operate under optimal conditions, resulting in the best performance in routine clinical tasks.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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