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Quality control in PET/CT and PET/MRI: Results of a survey amongst European countries

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ABSTRACT

Purpose: An EFOMP Working Group (WG) was created in 2020 to establish recommendations for PET/CT/MRI Quality Control (QC). The WG's intention was to create a document containing a set of measurements suitable for routine practice. In order to map the current situation in PET facilities, the WG prepared a survey addressed to European Medical Physics Experts (MPE).
Methods: The survey was conducted using an electronic questionnaire with 10 sections, for a total of 43 multiple choice or open questions. Data regarding general information, model of installed scanners, contract of maintenance and phantoms available were collected. The focal part of the questionnaire concerned the QC protocol adopted and accreditation programs.
Results: 123 answers from 24 countries were collected. 90.2% of the respondents are affiliated as staff MPEs; 45% have non-digital TOF PET/CT scanners with a contract of maintenance (97.6%). In 98.4% and 86.8% of responding centres a sealed source for daily QC and the NEMA Image Quality Phantom were present. 94.3% of respondents perform daily QC according to manufacturer recommendations, while NEMA Tests are not performed routinely (51.2%). 56.1% of the respondents have scanners accredited by a national or international organization. 56% of the centres perform annual CT tests, while more than 90% do not perform any MRI QCs.
Conclusions: The results of the survey show that there is a lack of harmonization in the PET QC procedures across Europe. The information obtained will guide the WG in proposing a guideline containing a set of measurements suitable for the clinical routine.

Introduction

Establishing a quality control (QC) program for Positron Emission Tomography (PET) scanners represents a crucial effort to ensure the correct diagnostic performance and quantitative accuracy.

The Council Directive 59–2013 [1], which issues basic safety standards for protection against ionising radiations for the Member States, also claims the implementation of appropriate quality assurance programmes for radiological equipment (Article 60), which is intended to provide adequate guarantee that a system performs satisfactorily in compliance with agreed standards. After the acceptance, a periodic QC programme is specifically required to test the constancy of the performance of the equipment throughout its lifetime.

Several recommendations by national and international agencies

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exist for periodic PET/CT QC, such as from the European Association of Nuclear Medicine (EANM) [2], International Atomic Energy Agency (IAEA) [3], American Association of Medical Physics (AAPM) [4] and International Electrotechnical Commission (IEC) [5]. Also National Electrical Manufacturers Association (NEMA) tests [6–8], which are intended to verify the performance of the PET scanner at its installation and acceptance, could be used as routine tests.

An effective QC program is able to detect subtle changes in the performance of the PET scanner, using simple, practical and reproducible procedures, and through the use of selected and measurable parameters directly linked to the quality of clinical images; in other words, it helps to detect problems before they can impact clinical studies in terms of safety, image quality, quantify accuracy and patient radiation dose.

In some situations, the Medical Physics Expert (MPE) may encounter difficulties in strictly following international recommendations when setting up a QC program. Invalaiability of specific software or phantoms is just one of the reasons. In addition, several technical advances in PET hybrid technology appeared during the last decade like digital PET/CT and PET/MRI, which are not always considered in QC guidelines. The scenario for PET/MRI QC is even worse, because of the lack of dedicated QC recommendations and phantoms for these hybrid scanners [9]. Technology also advanced in the way that QC can be performed, as using custom created 3D phantoms [10–12].

Another issue that has to be considered when setting up a QC program is the standardization of practices and quantification. These are crucial issues in PET imaging, as claimed by several scientific societies such as EANM, AAPM, American College of Radiology (ACR), Radiological Society of North America (RSNA) and Society of Nuclear Medicine and Molecular Imaging (SNMMI), [13–16]. The accreditation of PET/CT scanners is a way to guarantee the compliance with fixed standards and to favour the harmonisation of PET imaging among centres [17,18]. Several accreditation schemes like EARL [19,20], UK PET Core Lab [21], Italian Lymphoma group [22], SNMMI CTN [15], ACR [14] are avalaiable.

An EFOMP (European Federation of Organisations for Medical Physics) Working Group (WG) on PET/CT and PET/MRI QC was created at the beginning of 2020 with the aim to establish recommendations and procedures for PET/CT and PET/MRI QC, and to prepare a document with a set of measurable parameters suitable for a real routine practice.

In order to map the current situation on various types of PET facilities and to better focus on problematic parts of QC procedures, the WG prepared a survey addressed to European MPEs dealing with PET/CT and PET/MRI Quality Control. The information gathered helped in tailoring the future document to the routine practice, taking into account possible local variations based on the size of the hospital, type of the department/hospital (university/clinical), model of PET scanners, availability of various types of phantoms, radionuclide availability, adhearnce to accreditation programs, costs, time etc.

This paper describes the survey and analyses the collected data in the light of the Guideline on the QC on PET/CT and PET/MRI.

Materials and methods

The survey was conducted using an electronic questionnaire (via Google forms). The questions consisted of multiple choice and open questions. The open questions were used to collect comments and suggestions from the respondents. The survey was divided into 9 sections, for a total of 43 questions. The estimated time to complete the form was 5 min. Table 1 shows a detailed description of the questions.

General information as country, affiliation, hospital type and number of years of experience of the respondents were covered in Section 1. Data about the model and numbers of installed scanners were also collected, in order to know the distribution of the PET/CT and PET/MRI scanners throughout Europe.

Section 2 was aimed at obtaining information on both NEMA and custom 3D-printed phantom availability, while Section 3 addressed the PET daily QC test in terms of the used source types and metrics.

Section 4 of the survey was designed to investigate the aderhence to accreditation programs, namely the number of accredited PET scanners and the accreditation organization.

Accurate quantification in PET imaging is directly related to harmonization and depends on the accuracy of different components outside the imaging itself, such as radionuclide calibrators, weighing scales and clocks. Section 5 was dedicated to quantification in terms of tests performed on radionuclide calibrators, cross calibration between the radionuclide calibrator and PET scanner, clocks and weighing scales.

Section 6 was intended to survey whether and which NEMA tests were used as routine QC tests, which version of the NEMA guideline was followed and if any deviations from the guideline were introduced.

Additional QC tests can be performed depending on the clinical

Table 1
Section numbers, descriptions and questions of the survey. TOF: Time of flight, HU: Hounsfield unit, SNR: signal to noise ratio.

Section No.	Section description	Questions
2.1	General Information	• Country • Type of responder's affiliation • Type of the hospital • Years of experience in PET QC • Model of PET/CT system installed at the hospital • Number of scanners installed at the hospital • Age of the oldest PET scanner • Presence of contract of maintenance • Responsibilities for the QC
2.2	Phantoms	• Presence of sealed radiation source for daily QC • Other phantoms availability • Access to a 3D printer
2.3	PET Daily QC	• Perform daily QC or not • Source used in the daily QC • Metrics evaluated in the daily QC
2.4	PET Accreditation	• Accreditation by a national/international organization • Organization for the accreditation
2.5	PET Quantification	• Periodicity for cross calibration, clock test, accuracy of calibrator to primary standard, weighting scale accuracy
2.6	NEMA Performance test	• NEMA test perform routinely • Version of NEMA Standard used • Sphere to background ratio used for image quality • Periodicity for each test (image quality, spatial resolution, sensitivity, TOF resolution)
2.7	Additional performance test	• Perform routine performance test other than vendor or NEMA or not • Procedure for additional test • Periodicity of additional test • Additional test dedicated for radiotherapy applications
2.8	QC on the CT component	• Periodicity for short tube conditioning, air calibration, uniformity, HU water, noise, spatial resolution, image quality, CT dose, PET-CT alignment • Phantom for QC on the CT component • Source used for the PET-CT alignment • Annual test on CT following national guidelines or not
2.9	QC on the MRI component	• Perform QC on the MRI component or not • Frequency for uniformity, SNR, ghosting, geometrical distortion, slice thickness, slice warp, spatial resolution, geometry, PET-MRI alignment • Phantom for QC on the MRI component • Source for the PET-MRI alignment • Annual test on MRI following national guidelines

needs of the PET centre, especially when PET/CT and PET/MRI imaging is used for volume delineation in radiation therapy planning [23]. Section 7 was designed to collect information on this topic.

As a hybrid technology, routine QC tests are also important on the CT and the MRI component to guarantee the overall image quality of the entire system. Sections 8 and 9 were dedicated to collect information on the QC tests and their frequency performed on CT and MRI scanners.

The survey was send to the EFOMP ing list of European MPEs between June and July 2020 using a Google Form link. Data were processed anonymously, checking that no overlapping information or multiple incomplete forms from one user was present. Aggregated data were presented in terms of absolute and relative frequencies (reported as percentages), pie charts and histograms.

Results

General information

The questionnaire was closed after by collecting 123 answers from 24 different countries between the 27th of May to the 14th of August of 2020. The distribution of answers from different countries is reported in Table 2.

The responders are mostly affiliated as staff MPEs (111, 90.2%), while a small fraction of them (7, 5.7%) are consulting MPEs or belong to other affiliations (5, 4.1%). The respondents worked in University Hospitals (58, 47.2%), Hospitals (52, 42.3%), Cancer Centres (13, 10.6%), Private Clinics (9, 7.3%) or Research Laboratories (5, 4.1%) with some of them having multiple employers. The median years of experience with PET QC was 10 years (range 0–36 years). The experience with GE Healthcare, Siemens Healthineers, Philips Healthcare and Canon systems was present in the 60.3%, 55.4%, 30.6% and 1.1% of respondents respectively.

Type and age of scanners are reported in Fig. 1.

The majority of the centres (120, 97.6%) has a contract for maintenance on their scanner. The routine QC (other than daily ones) were performed by MPEs (106, 86%), manufacturers (42, 34%), technologists (37, 30%), medical engineers (7, 6%) and PET operators (1, 1%), with some multiple answers.

Phantoms

The majority of the responding centres (121, 98.4%) have a sealed source for daily QC, which is periodically replaced according to the manufacturer recommendations. Phantom availability, reported in Table 3, differs significantly among centres. Access to a 3D printer for creating customized phantoms is limited (91, 75.6% do not have availability of these systems).

Table 2
Number and frequency of answers from different countries.

Country	No.	Frequency (%)
Italy	23	18.7%
France	20	16.3%
Netherlands	20	16.3%
United Kingdom	18	14.6%
Greece	9	7.3%
Spain	5	4.1%
Czech Republic	5	4.1%
Austria	3	2.4%
Belgium	3	2.4%
Norway	2	1.6%
Poland	2	1.6%
Country	**No.**	**Frequency (%)**
Others (Bahrain, Croatia, Cyprus, Estonia, Germany, Lithuania, Malta, Moldova, Portugal, Singapore, Sweden, Switzerland)	13	10.6%

PET daily QC

94.3% of centres perform daily quality control according to manufacturer's recommendations, using a sealed source and the pre-defined protocol. The type of radioactive sources used for the PET daily QC are reported in Supplemental Table 1.

PET accreditation

Only 56.1% of the centres have PET/CT or PET/MRI scanners accredited by a national or international organization (Fig. 2).

PET quantification

The QC tests related to PET quantification showed a wide range of performance frequency, with the exception of the cross calibration test. The majority of the respondents cross-calibrate the PET scanner using ^{18}F on a quarterly basis (60%), followed by an annual (14%) and after major intervention (8%) run, as shown in Fig. 3.

The clock test is performed fairly equivalently on daily (19%), monthly (18%), weekly (17%) and quarterly (26%) basis, the minority of the respondents perform this test annually (3%), after major intervention (10%) or never (7%).

The accuracy of the radionuclide calibrator measurements using a primary standard is mainly performed on a daily and annual basis (26%), followed by quarterly (12%), after major intervention (10%), monthly (6%) or weekly (4%). Of the responders 8% never perform this test.

Finally, the accuracy of the weighing scales is mainly performed on an annual basis (36%), but 32% of responders never perform this test. A small fraction of the respondents performs the test quarterly (8%), daily and monthly (4%) and weekly (2%).

NEMA performance test

The 51.2% of the centres do not routinely perform NEMA tests. From centres that do perform them, 60.0% follow the NEMA NU-2012 standard [7], 28.3% the NEMA NU-2007 [6] and the 20.0% the NEMA NU-2018 standard [8] (multiple answers were possible). Periodicities of the image quality and correction accuracy, spatial resolution, sensitivity and TOF resolution test are reported in Supplemental Fig. 1. All tests are performed mostly as annual tests, although there is a disparity in the frequency of tests' acquisition. Whereas the image quality and correction accuracy is performed on an annual basis by the 82% of responders, only 40% of responders perform the scatter fraction and count rate annually. TOF resolution, recently added to the NEMA standards and applicable only to TOF systems, is annually checked by the 26% of responders. The major difficulties in performing NEMA tests reported by the respondents are collected in Table 4.

Additional performance test

38.2% of the respondents perform additional tests other than the vendor's suggested and NEMA tests, most following local protocols (36%), EARL (EANM Research Ltd) (21%) or country specific guideline (16%). Dedicated QC for radiotherapy applications were reported in the 25.5% of responses.

QC for the CT component

Frequencies related to QC on the CT component (short tube conditioning, air calibration, uniformity, accuracy of HU of water, noise, spatial resolution, image quality, CT dose and PET/CT alignment) are summarized in Supplemental Fig. 2. A large discrepancy can be observed

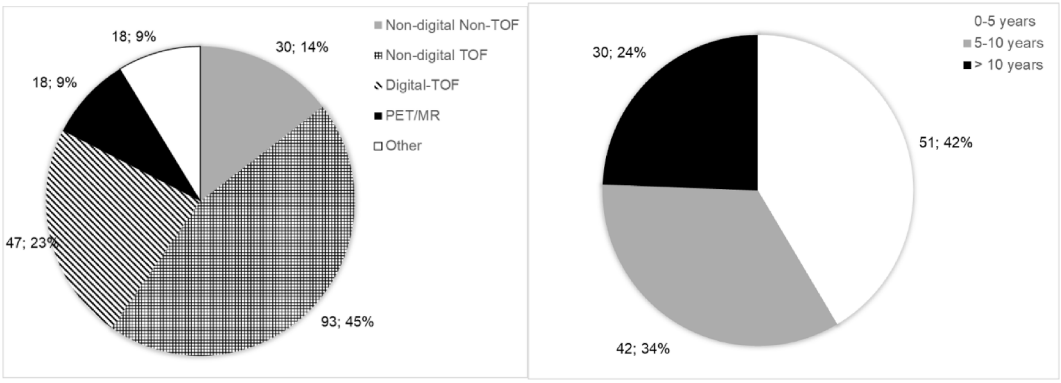

Fig. 1. Type of scanners (left) and age of scanners installed (right) with absolute frequencies and percentages;"Other": dedicated or small-animal PET system; "Digital": PET scanner with silicon photomultiplier detectors [24].

Table 3
Phantom availability among PET centres.

Phantom type	No.	Frequency (%)
NEMA Image quality phantom	79	86.8%
Jaszczak phantom	61	67.0%
NEMA Sensitivity phantom	58	63.7%
NEMA Scatter phantom	55	60.4%
NEMA Resolution phantom	50	54.9%
Micro hollow sphere	21	23.1%
Hoffman brain phantom	21	23.1%
ACR phantom	9	9.9%
Others	11	12.1%

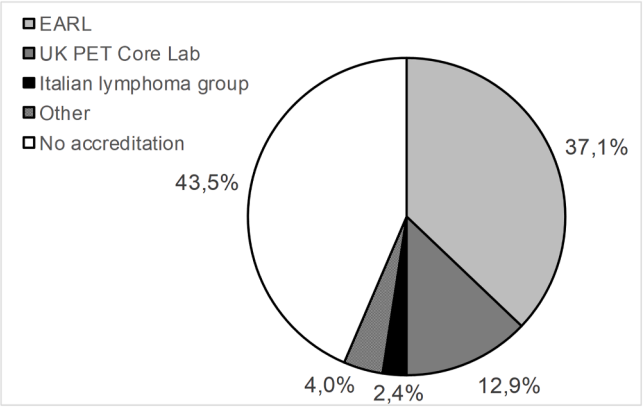

Fig. 2. Type of PET accreditation schemes.

between the frequencies for most tests. Additionally, 56% of the centres perform annual CT test following national guidelines. Most respondents perform the PET/CT alignment with sealed radioactive sources as two or three ^{68}Ge rods or six ^{22}Na point sources.

QC for the MRI component

More than the 90% of the respondents do not perform any quality control tests for the MRI component. The reported frequencies related to QC on the MRI component (uniformity, SNR, ghosting, geometrical distortion, slice thickness, slice warp, spatial resolution, geometry, transmitter frequency and PET/MRI alignment) are summarised in Supplemental Fig. 3. Similar to the CT component, large variations in the periodicity of the tests can be observed. The most frequently used phantoms for the MRI QCs are the ACR (6, 42.9%) [25], the Spinsafety (2, 14.3%) [26] or vendor specific (8, 57.1%) phantoms. The majority of the respondents use radioactive sealed sources for the PET/MRI

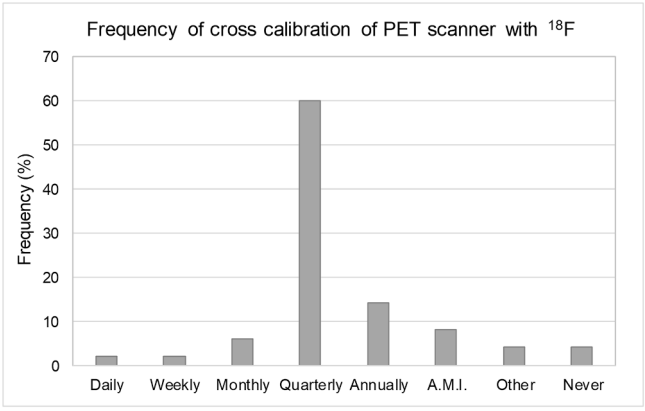

Fig. 3. Frequencies of the cross calibration of the PET scanner using ^{18}F (AMI: After major intervention).

Table 4
Difficulties in performing NEMA tests.

Type of difficulty	No.	Frequency
Phantom preparation	14	44%
Data analysis	9	28%
Acquisition setup	7	22%
Fragility of the phantom	1	3%
Time allocation to perform QC	1	3%

alignment (mostly two or three rods of ^{68}Ge sources). Only 23.1% of the respondents perform annual MRI test following national guidelines.

Discussion

This paper summarizes the results of the EFOMP WG on PET/CT and PET/MRI QC survey conducted in 2020. Data were collected from a significant number of PET centres. This gives a reliable picture of the overall situation on the quality control tests performed on PET/CT and PET/MRI scanners in Europe.

The survey showed a considerable variability in the type and age of PET scanners installed in Europe. There is still a large pool of older systems and non-TOF PET systems, which makes it necessary to adapt QC tests to the different types of the equipment installed.

Another important issue that must be considered when developing a practical QC protocol is the availability of phantoms. The survey shows that not all phantoms are equally available: the most common is the NEMA Image Quality (86.8%), indicating that this phantom can be used in a QC program, probably without the combined use of the scatter

phantom which is present only in the 60.4% of the respondents' PET centres. Only a few PET centres have micro hollow spheres (23.1%), a Hoffman brain phantom (23.1%) and/or the ACR phantom (9.9%), making it undesirable to consider this phantoms for QC.

Nowadays, 3D printers offer the potential for developing CT, PET and MRI phantoms tailored for the user's need and with limited costs [10–12]. Nonetheless, some limitations in 3D printed phantoms are still present, mainly related to the limited knowledge of the properties of the materials used and the presence of air bubbles that may affect the image quality [10]. However, our data showed that only 25% of the respondents have access to 3D printers, demonstrating that this solution is not still sufficiently widespread to play a role in a QC program.

Almost all of the centres (94.3%) perform the routine or daily QC on the PET/CT and PET/MRI systems using sealed sources following the manufacturer's protocol. This may be related to the fact that in many scanners the successful result of the daily QC test is a pre-requisite for performing clinical studies. In a QC program, the importance of a daily QC test must be underlined. The daily QC procedure is nowadays nearly automatic, ensuring a high level of reproducibility and generally preventing errors in source acquisition and/or image processing.

Several scientific societies such as EANM, ACR, AAPM, RSNA and SNMMI continuously promote standardisation of practices in order to reduce variability of quantification in multicentre clinical trials. Accreditation of PET/CT scanners with programs such as QIBA [16], SNMMI [15], EANM-EARL [19], Italian Lymphoma Group [22] and UK PET Core Lab [21], the Grupo Español de Linfomas/Trasplante Autólogo de Médula Ósea (GELTAMO) group [27] is a way to guarantee the compliance with fixed standards and to favour the harmonisation of PET imaging among centres. More than half of the respondents followed an accreditation program for their PET/CT scanner; for the majority of them EARL is the reference (37.1%) followed by UK PET Core Lab (12.9%) and Italian lymphoma group (2.4%). A significant part of the respondents (44%) still did not follow any accreditation scheme.

In this regard, there is still work to be done for the different accreditation entities in terms of presenting the programs more feasible to the different nuclear medicine departments in order to further extend their implementations.

One of the added values of PET studies is the possibility to easily quantify the radiopharmaceutical uptake in organs and tissues and to use standardized uptake values (SUVs) as a non-invasive quantitative imaging biomarker for patient staging and follow up. On the other hand, several factors may influence the variability in SUV measurements.

The first factor that may affect the quantification accuracy is the radionuclide calibrator. Calibrator accuracy should be part of the PET centre's QC program, especially when radionuclides other than ^{18}F are used [28,29]. In addition, to obtain reliable and comparable intra and inter-equipment data, cross-calibration between the PET scanner and the radionuclide calibrator has to be performed on a regular basis. Despite most centres performing a quarterly cross-calibration of the PET scanner using ^{18}F, the attitude to calibrators accuracy test differs significantly among centres, with approximately the same number of departments performing it on a daily or an annual basis (26% in both cases). The verification of the weighting scale accuracy, that often represents a neglected cause of SUV variability [30], is also performed with a variable periodicity, mostly annual (36%), but one third of the centres had never checked it. The clock calibration test is performed by 80% of the centres, mostly quarterly.

Some routine QC tests may be based on an adaptation of the NEMA tests performed during the acceptance testing of the scanner [6–8]. As previously described, approximately half of the centres, which responded to this survey, do not carry out routine NEMA Performance Tests. The most common reason is the difficulty in preparing the phantoms (44%), including the radionuclide availability. Another concern arises with the image quality test, where about the 60% of the respondents lack the scatter phantom. Thus simplifying the phantom preparation by removing the scatter phantom from the acquisition setup, will increase feasibility of the process, reduce the preparation time and, consequently, the personnel irradiation and the risk for radioactive contamination. Data analysis and acquisition setup represent other relevant concerns (28% and 22% of the respondents, respectively) in following NEMA procedures: frequently, acquisition, reconstruction, and analysis software are not available for the regular user without the vendor's support (i.e. to analyse raw PET data for scatter fraction and count rate).

PET is a hybrid imaging technique and with regards to the QC of the CT or MRI component, some concerning aspects emerged from the survey results. Only 56% of the centres perform annual CT tests following national guidelines. This could be partially explained as a poorly-framed question, as some countries may not have national guidelines. There is also a lot of variability in test frequency, which shows the need for proper harmonization in the QC procedures. For PET/MRI scanners, more than 90% of the respondents do not perform any QC for the MRI component. A possible explanation of this result may be that the QC of the CT or the MRI component could be performed by the MPE in charge of the radiological equipment and not by the MPE dedicated to the nuclear medicine/PET department, who participated in the survey. Another reason for this might be because the quality control of MRI devices is not frequently carried out by physicists and not firmly encouraged by manufacturers. Indeed, it is generally considered that the clinical routine makes it possible to detect the majority of MRI defects.

In conclusion, the results of the survey show that there is a lack of harmonization in PET QC procedures in across Europe. The lack of standardization was already reported in literature. Rausch et al [31] conducted a survey in Austria in 2014. The authors highlighted a great variation in both the frequency of QC tests and in the results of the recovery coefficients in phantom measurements, claiming the need for improving the accuracy. Multiple reasons can lead to such divergences in QC practices. Adequate QC still depends to a large extent on the awareness of each centre's medical and financial departments on the necessity to perform such procedures, as well as the availability of expert staff, namely the number of MPEs.

A limitation of the survey could be an occasional misinterpretation of the question, although in vast majority of the sections clear answers and results were obtained. In addition, the present questionnaire was filled only by medical physicists and hence could not include potential centres that don't perform QC routinely. Finally, specific questions related to new large axial FOV or total body PET systems [32] were not included; for this new type of technology, a dedicated analysis on the QC, that are specific for these systems, will have to be carried out.

Conclusions

The information obtained from the questionnaire will guide the WG in proposing a guideline containing a set of measurements suitable for the clinical routine for most of the MPEs.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejmp.2022.05.004.

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