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Original Paper

Patient-specific quality assurance in stereotactic radiotherapy: clinical practice in absence of guidelines – status and new approach from the DGMP working group for physics and technology in stereotactic radiotherapy

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ABSTRACT

Introduction: Guidelines on how to perform patient-specific quality assurance (PSQA) in stereotactic radiotherapy (SRT) are currently not available. In this context, guidelines for modulated techniques like IMRT or IMAT do include descriptions of PSQA. However, commonly used quality assurance (QA) devices, methods, and evaluation metrics are not sufficiently suitable for small-field conditions. Consequently, these guidelines cannot generally be applied to stereotactic radiotherapy.
The aim of this work is to assess the limitations of current clinical practice and provide guidance on choosing QA methods given the extensive QA requirements. Additionally, we will present a method for evaluating comprehensive PSQA programs, identifying blind spots, and supporting the selection of suitable devices and methods to overcome them.
Methods/Results: We reviewed available literature, especially guidelines, and identified main issues in today's PSQA practice for SRT by performing surveys among users and vendors. Current QA equipment, software, and methods were assessed and analyzed. Independently, we defined the scope of an appropriate PSQA for SRT. Subsequently, we related this to available devices and methods in a vendor-neutral manner, resulting in a toolkit for evaluation of site-specific PSQA programs in SRT. The approach and result were reviewed by a group of experts.
Discussion/Conclusion: No single QA solution or method can account for all PSQA needs for SRT. In addition, properly choosing PSQA evaluation metrics is key for a meaningful verification process. The heterogeneity of SRT implementations throughout different sites encompasses different needs and hinders the creation of a static guideline. In the absence of such, we derived a best option decision-making toolkit for optimizing a PSQA program to be used in the environment of stereotactic radiotherapy.

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1. Introduction

Quality assurance (QA) in radiotherapy purely serves patient safety. It should encompass all procedures and all groups of staff in a cooperative approach to ensure consistency of medical prescription and its safe fulfillment. Due to today's highly complex treatment methods, proof of adequate quality of the system of choice and the associated treatment chain is important and demanded by radiation protection legislation [1–3]. For the definition and standardization of radiotherapy practice, including treatment techniques, QA goals and quality measures, guidelines and consensus statements have been published by national and international organizations and societies [4–19]. Unfortunately, all these focus on either stereotactic or modulated techniques separately. The combination of both, in particular patient-specific quality assurance (PSQA), has not yet been assessed. Therewhile, the use of small, modulated fields is challenging for irradiation systems as well as for QA systems and methods. Many verification procedures struggle due to the high demands on small field dose accuracy, spatial resolution, and methodological requirements.

PSQA in general should aim for the determination and absolute quantification of a planned 3D dose distribution and its spatial relation towards the treated volume (TV) and organs-at-risk (OAR) throughout a treatment series. This requires an extensive approach that addresses not only a proper plan delivery verification, but also adequate machine commissioning, treatment planning system (TPS) beam modeling, data transfer, patient positioning/monitoring and changes in patient anatomy (Fig. 1).This listing is supposed to reflect the most relevant sources of errors in terms of severity, occurrence, and detectability [20,21]. In

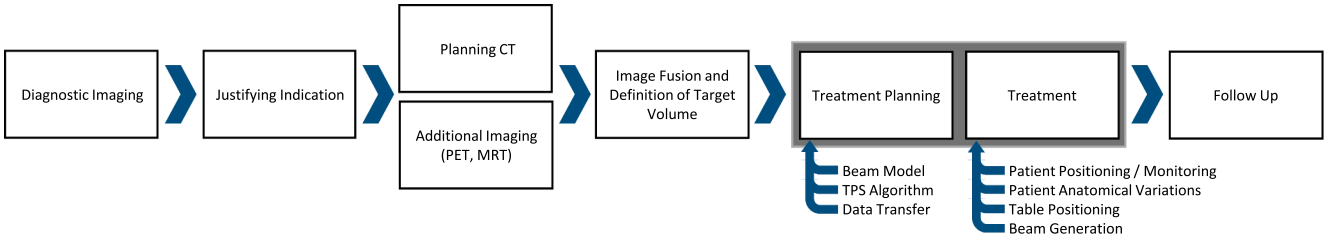

Fig. 1. Treatment chain in SRT. The highlighted points can be covered by PSQA as described in this article.

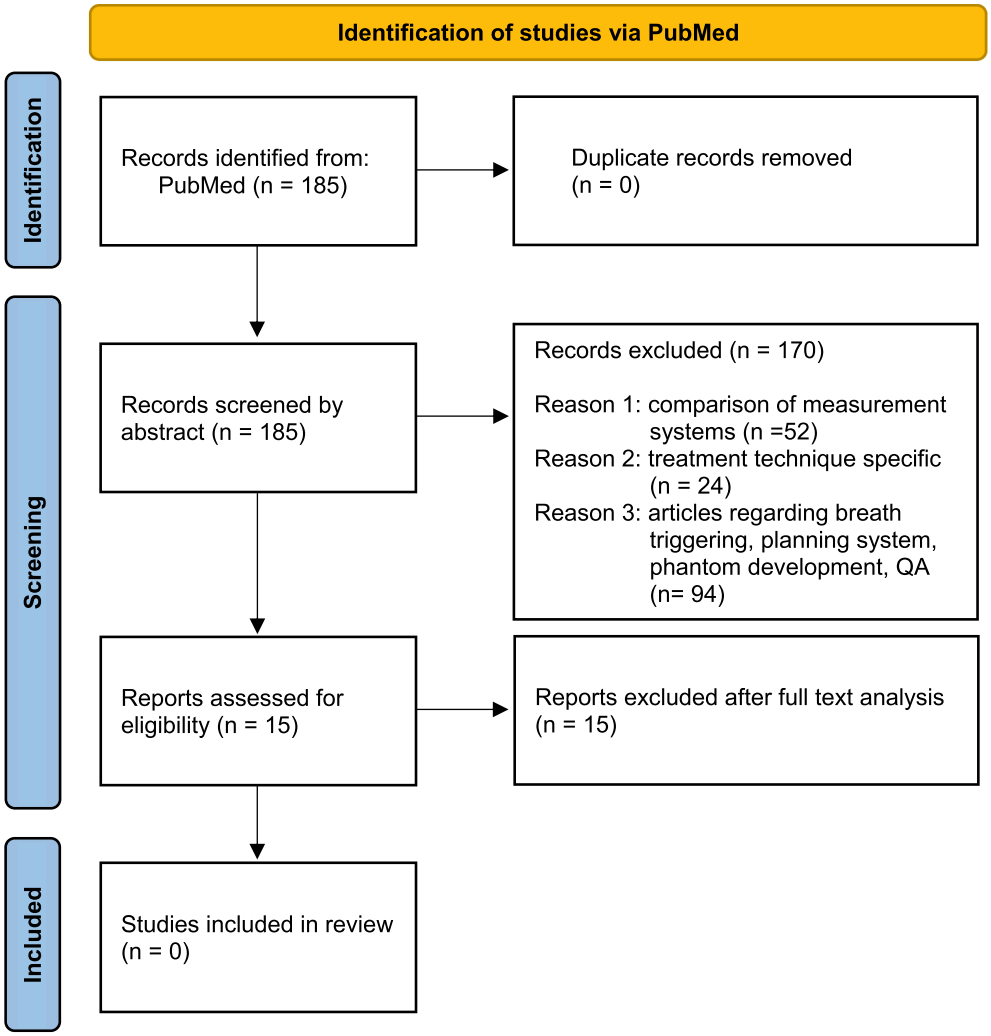

Fig. 2. PRISMA diagram [50] on PSQA guidelines for SRT.

distinction to this, further QA of the instruments required for PSQA, such as dose detectors, primary imaging devices (CT, MRI scanners), image guided radiotherapy (IGRT) systems, surface guided radiotherapy (SGRT) systems and the treatment chain, including machine QA and metrological inspections, is not specifically addressed here. Regardless, the transition is gradual and unless otherwise specified, the term "PSQA" in this article refers to PSQA for SRT.

As recently shown again, the interpretation and implementation of SRT varies significantly between clinics [21]. For Germany, the DEGRO/DGMP definitions and requirements for SRT [4,5] on top of the ICRU Report 91 [6] provide a general framework, but specific details regarding technology, equipment, patient monitoring systems and PSQA have been left open. The aim of this work was to investigate the status of PSQA in German speaking countries. This process was gradually immersed in the intricacies of the subject matter, ultimately facilitating the development of a comprehensive approach to address PSQA in a systematic manner.

We followed six fundamental milestones for this project of the DGMP Working Group for Physics and Technology in Stereotactic Radiotherapy:

- Literature overview and listing and sorting of relevant guidelines in the regime of PSQA and/or SRT (*Section 2.1*).
- Survey on the status of PSQA in German speaking countries and identification of main issues in current PSQA (*Section 2.2*).
- Market evaluation and unified listing of hardware- and software-based PSQA devices (*Sections 2.3 and 2.4*).
- Defining the core QA characteristics and setting the scope for PSQA (*Section 2.5*).
- Evaluation of vendor-neutral QA methods with respect to their suitability for verifying the predefined QA characteristics, resulting in a toolkit for selecting appropriate PSQA methods (*Section 2.6*).
- Review of the findings by a group of experts in stereotactic radiotherapy (*Section 2.7*).

2. Methodological approach

2.1. Preparatory work: literature overview – regulations and guidelines on PSQA for SRT

We conducted a literature review to identify guidelines on PSQA and studies describing how QA should be implemented in SRT. A PRISMA analysis based on a PubMed search was performed (Fig. 2) using the following query: ("quality assurance" OR "QA") AND ("patient-specific" OR "PSQA" OR "plan QA" OR "Plan-QA") AND ("stereotactic" OR "SRS" OR "SRT" OR "SBRT") for publication dates from 01/01/2010 to 31/08/2025. This resulted in a total of 185 articles being found.

Of these, 52 articles discussed or compared measurement systems, 24 were treatment- or machine-specific, 24 addressed treatment techniques, 94 examined planning systems, phantom development or respiratory motion management, and their influence on PSQA. All of these articles were excluded after abstract screening because they addressed specific PSQA aspects only and did not provide a comprehensive PSQA perspective.

Fifteen articles went beyond the scope of traditional plan QA. This included surveys, publications on modulation degree of treatment plans, action limits and tolerances, adopted gamma criteria, imaging, tracking and PTV/OAR generation. These articles were excluded after full text review because they did not provide sufficiently comprehensive recommendations in accordance with our predefined aim. As a result, no comprehensive recommendation or guideline on PSQA for SRT has been found.

2.1.1. Compilation of current regulations and guidelines on PSQA or SRT

Given this lack of comprehensive SRT-specific PSQA guidelines, we compiled a list of current regulations and guidelines relevant to PSQA or SRT. It was reviewed by experts (see Section 2.7), and supplemented with the reviewers' suggestions.

a) *Regulations and Guidelines on PSQA in IMRT/IMAT*

In Germany, the most significant guidelines on patient QA in intensity modulated radiotherapy/arc therapy (IMRT/IMAT) are German standards DIN 6875-3 (2008) [10] and DIN 6875-4 (2011) [11], which define verification requirements for modulated treatment techniques; both are currently under revision. Internationally, three AAPM Task Group reports are of relevance: TG-218 (2017) [14] for measurement-based IMRT verification, TG-219 (2021) [15] for calculation-based verification, and TG-307 (2023) [16] for plan verifications using electronic portal imaging devices (EPIDs).

b) *Regulations and Guidelines on SRT*

Several guidelines address SRT comprehensively, encompassing distinctive requirements for treatment planning, machine QA, and delivery. These guidelines support implementation and optimization of stereotactic practice but do not define a dedicated PSQA workflow. The DGMP consensus review on technological quality requirements for stereotactic radiotherapy [5] is regarded as the primary German reference and a precursor to the present work. Earlier German standards, DIN 6875-1 (2004) [8] and DIN 6875-2 (2008) [9], specify constancy checks for SRT and are likewise currently under revision to reflect evolving clinical and technological practices. DIN 6809-8 (2021) [22] addresses small-field dosimetry, a fundamental prerequisite for reliable SRT dose measurement.

Internationally, ICRU Report 83 (2010) [23] and ICRU Report 91 (2017) [6] establish principles for dose prescription and documentation in IMRT and SRT. Both reports underscore the need for machine-specific and patient-specific QA. AAPM TG-105 [17] provides guidance on the clinical implementation of Monte-Carlo-based treatment planning, which has been increasingly adopted in SRT owing to its accuracy in small, heterogeneous fields.

The AAPM-RSS Medical Physics Practice Guideline 9.a/9.b [12,13] (2017/2025) is one of the few guidelines that explicitly address patient QA in SRS and SBRT. It emphasizes the importance of PSQA in high-precision treatments, but does not offer detailed procedural guidance.

2.1.2. Summary

Currently there are no dedicated guidelines addressing PSQA specifically for SRT. The available literature either focuses broadly on SRT or examines PSQA in the context of modulated techniques (IMRT/IMAT) yet rarely encompasses both. Existing literature specifically addresses certain treatment machines, -techniques or measurement devices. Consequently, the aforementioned documents constitute the most comprehensive current framework for PSQA in SRT, though important deficiencies remain. They provide only a fragmented framework for PSQA in SRT and offer limited guidance for its implementation in daily clinical practice. This raises the question of how PSQA for SRT is currently implemented in the clinical setting.

2.2. Preparatory work: user survey on PSQA for SRT

Despite the absence of dedicated guidelines, PSQA in modulated SRT is widely recognized as an essential component of safe clinical practice. To assess the scope of clinical implementations, we designed a survey on

plan verification for SRT. It was conducted among the DGMP Working Group for Physics and Technology in Stereotactic Radiotherapy/DEGRO community from 2020 to 2021 and covered general questions on SRT implementation [(3)], detailed questions about plan-QA practices [(4)], and the perceived necessity, advantages, and limitations of these practices. The original idea of the survey was to establish a basis for a potential guideline and thus to help close the aforementioned gap. As a preliminary remark, it should be noted that at the time this survey was conducted, the term PSQA was equivalent to plan-QA.

In the survey, a total of 43 users from Germany, Switzerland, and Austria participated. Most centers performed PSQA according to guidelines for IMRT/IMAT. Detector arrays or electronic portal imaging devices (EPIDs) were the most used tools. Independent secondary dose calculation was also used as a complementary method at many centers. Most sites based their PSQA pass/fail decisions on gamma analysis [24,25], which combines dose-differences (DD) and distance-to-agreement (DTA) thresholds into a pass-fail decision for every dose voxel. In most centers, identical DTA and DD criteria were used for SRS and SBRT. Typical settings reported in the survey were 1–3 mm (DTA) and 1–3% (DD). Alternative approaches, such as dose-volume histogram (DVH)-based decision making, played only a minor role. All results of the survey are provided in the supplement.

2.2.1. Considerations for the use of gamma analysis

In recent decades, the gamma index [26,27] has become a widely used tool for comparing measured and calculated dose distributions in IMRT/IMAT, and it is now also the standard metric in many SRT plan verification workflows. Our survey confirms this trend: almost all participating centers rely on gamma analysis as their primary criterion for plan acceptance. The reported workflows were generally thoughtful and were not fundamentally inappropriate, but some aspects were questionable, such as the use of standard IMRT/IMAT criteria also for SRS with 3% DD and 3 mm DTA and the limited differentiation between SBRT and SRS.

In general, the gamma method provides only a global, statistical metric with several well-known limitations [12,26–29]. The reported passing rates depend strongly on the specific analysis conditions and implementation details. Relevant factors include, for instance, the evaluated dose matrix volume relative to target and OAR volumes, the applied low-dose threshold, the choice between global and local normalization, the detector system resolution, and the analysis algorithm settings. Gamma statistics can underestimate the clinical impact of local dose delivery errors [30,31]. Conversely, local gamma “failures” may correspond to lower-than-planned OAR doses and thus be clinically preferred.

AAPM TG-218 (IMRT) [14] has already stressed that thresholds, dose normalization, as well as analysis settings must be chosen thoughtfully, so that users should not rely on a single passing rate alone. This is particularly relevant for SRT, which is delivered closer to technical and geometric limits. The characteristics of SRT dose distributions impose additional constraints: in regions with steep dose gradients, gamma effectively transforms into a pure DTA test, which can obscure local dose differences for directly adjacent or overlapping OARs. Accordingly, the suitability of gamma analysis as the primary or even sole metric for stereotactic plan verification must be carefully reconsidered. Advanced evaluation methods, such as DVH-based assessment of PTV and OAR doses, are not yet widely used in routine plan verification. For SRT, additional criteria may also be considered, such as verifying conformity-, gradient- and other quality indices [32–34].

The outcome of gamma analysis also depends on the measurement system. Using identical gamma criteria with different detector geometries and sampling schemes can produce systematically different passing rates. Coarse detector spacing combined with loose DD/DTA criteria shows poor sensitivity to millimeter-scale multi-leaf collimator (MLC) errors [28,35]. Our survey shows frequent use of detector arrays and EPIDs. Arrays designed for larger-field IMRT QA may lack the spatial resolution required for SRT, and EPIDs can also be problematic in small fields due to limited scatter volume [16,36,37]. Thus, detector characteristics must always be considered when interpreting measurements.

2.2.2. Secondary dose calculation

The survey shows that, in addition to measurement-based QA, independent secondary dose calculation has become a significant component of PSQA. AAPM TG-219 [15] and several recent clinical studies recommend calculation-based dose verification on the patient CT with an algorithm and beam model that are independent of the treatment planning system’s and validated for small fields. These systems can help to validate plans and reduce the number of measurements without compromising error detection, but they do not test the mechanical delivery chain and therefore cannot replace measurement-based SRT PSQA in general.

2.2.3. Survey findings and limitations for guideline development

Altogether, these observations explain why the survey does not provide a sufficiently robust basis for a concrete recommendation or guideline on patient-specific QA in SRT. The heterogeneity of stereotactic practice limits the feasibility of uniform recommendations: SRT indications range from single-fraction SRS for multiple brain metastases to multi-fraction SBRT of extracranial lesions with comparatively larger margins. The corresponding treatment geometries include plans with an isocenter positioned far from the target volume, targets adjacent to or overlapping with organs at risk (requiring simultaneous integrated protection, SIP), and targets located far from critical structures.

The survey emphasizes the importance of improving our understanding of the strengths and weaknesses of the current QA tools, rather than defining a single prescriptive standard. Therefore, we conducted a vendor survey of measurement devices and secondary dose-calculation software (Sections 2.3 and 2.4) and developed a matrix-based framework that maps different QA methods to the various components of a comprehensive patient-specific QA process (Sections 2.5 and 2.6).

2.2.4. Summary

The survey among German speaking physicists shows that SRT PSQA in clinical practice is dominated by detector array- or EPID-based measurements evaluated by gamma analysis, while secondary dose calculation has become a complementary component at many centers. According to our survey the gamma analysis is typically applied with identical criteria for SRS and SBRT (DD 1–3%/DTA 1–3 mm) and in some cases, less stringent criteria such as 3% (DD)/3 mm (DTA) are still used for SRS. Moreover, the gamma index is a global, statistical metric with known limitations, and its passing rate depends strongly on analysis settings and detector properties. Gamma results must therefore always be interpreted in the clinical and technical context of the individual case.

Relying on a single gamma passing rate for plan acceptance is not recommended, especially in stereotactic scenarios. The high precision requirements for SRT further underscore the need for a broader view of patient-specific quality assurance that goes beyond plan validation alone. Consequently, the survey results do not provide a sufficiently robust basis for a single, prescriptive guideline on patient-specific QA in SRT but rather motivate the extended assessment presented in the subsequent sections.

2.3. Vendor query: measurement hardware and analysis software

The capabilities and limitations of available measurement hardware

[(3)] e.g., irradiation devices, medical indications, irradiation techniques, imaging methods, and quantity

[(4)] e.g., the method and equipment used, frequency, and evaluation criteria

and accompanying analysis software strongly influence the range of possible approaches for performing PSQA. Consistently, James et al. [38] reported that SRT plan-evaluation outcomes strongly depend on the detector system and analysis workflow. This raises the practical question of hardware suitability for PSQA in SRT. We therefore designed a vendor questionnaire to collect the technical features of available QA equipment commonly used in German-speaking countries. Vendors whose equipment is widely used in these regions were invited to participate. The questionnaire covered the technical characteristics of measurement hardware and its dedicated software. Participants were requested to report only solutions deemed appropriate for SRT, including SRS.

Replies from nine vendors were collected, comprising 19 measurement devices and 10 software tools. Measurement devices that support spatially resolved measurements, thus enabling at least 2D dose distributions, were considered. The results shown in Table 1 and Table 2 were approved by the vendors in January 2024. In view of ongoing technological developments, we cannot claim that this data is completely up to date, but we used it in its entirety for vendor-neutral conclusions that we consider valid as of today. Table 1 provides an overview of commercial SRT PSQA equipment, including detector arrays, linac-integrated EPID systems, and third-party EPID-based solutions. Table 2 covers software tools for measurement-data processing and analysis for the aforementioned systems, including availability of 2D/3D gamma analysis and configurable options. Both tables contain vendor-supplied data. Inclusion does not imply suitability for stereotactic PSQA.

Passive systems like radiochromic film-based dosimetry (film-QA) [39,40] and gel dosimetry [41,42] were not included in this compilation since they were rarely mentioned in the user survey on PSQA (Section 2.2). Even though they set a benchmark for spatial resolution and absolute-dose discrimination, they can hardly be compared in specifications to active systems. The relation of different detector concepts will be assessed in more detail in Section 2.6.

In addition to this survey, it should be noted that Malatesta et al. [43] conducted a systematic review based on the PRISMA method. Their review included 36 studies from 2010 to 2022 and summarized device and method characteristics for measurement-based SBRT PSQA.

2.3.1. Summary

Currently, nearly all major QA vendors with a strong presence in German-speaking countries offer measurement devices specifically designed for SRT PSQA. Most of these devices use detector arrays with small detector spacing or electronic portal imaging devices (EPIDs), which allow for high-resolution measurements. However, these systems lack dosimetric accuracy at small field sizes (see Section 2.2.1).

No current device offers real 3D information. Therefore, e.g., off-center measurements concerning treatment plans for multiple brain metastases require special care with most systems [42], such as combination of prolongated multiple detector angle measurements or other workarounds. Most available evaluation software relies mainly on gamma analysis as plan acceptance criterion. This approach provides limited information about the reasons and clinical relevance behind any discrepancies, as discussed in Section 2.2.

2.4. Vendor query: secondary-dose calculation software

Independent secondary-dose calculation has become a meaningful complement to measurement-based PSQA [44,45]. Using its own algorithm and beam model, this approach verifies aspects that detector-based measurements cannot assess, such as algorithm consistency, small irradiation fields, handling of heterogeneities and others. In addition, it offers full 3D dose information. Although it cannot fully replace QA measurements, it adds clear value to PSQA.

To further investigate these systems, we conducted a survey among ten vendors providing secondary dose calculation software and compared the functionalities and limitations of their products. The responses were compiled and standardized in Tables 3.1 and 3.2, subsequently reviewed and approved by the vendors in August 2024. Table 3.1 shows general properties of each software, such as implemented algorithms, supported treatment units, and details about the commissioning process. Table 3.2 lists data processing attributes, including the minimal dose grid resolution, options for DICOM-compliant dose export, and functionalities like DVH or gamma analysis.

2.4.1. Summary

All surveyed QA vendors have been offering or are currently developing Monte Carlo based recalculation software to account for exact cross sections for all relevant particle interactions. This enables exact dose calculation even for the smallest fields. For PSQA result evaluation, all vendors provide a gamma-based ‘pass/fail’ decision. Additionally, all vendors provide 3D dose- and DVH-comparisons, which measurement-based solutions can hardly offer (see Section 2.3).

Secondary-dose calculation offers a fast and precise, treatment-planning-system (TPS)-independent way to check dose distributions. It can be automated and run in the background, enabling time-efficient QA for large numbers of plans and tight treatment scheduling. As a drawback, it covers only aspects of plan-QA and dose verification. It does not capture machine-, imaging- or patient-related issues. Therefore, it should be combined with measurement-based methods to obtain a comprehensive PSQA program as shown later in Section 2.6.

In terms of plan-QA only (not PSQA), discussions are currently underway to determine the extent to which recalculation QA can reduce measurement effort without compromising the reliability of results [44–46].

2.5. Deriving a new approach from existing standards: definition of QA characteristics

We assessed the status of PSQA by reviewing the clinical practice of plan verification and relevant literature (Section 2.1 and 2.2) and by surveying the market for equipment and software (Sections 2.3 and 2.4). In view of the heterogeneity among sites as well as identified gaps in formal guidelines, we introduce a list of “QA characteristics” that reflects what we suggest a comprehensive PSQA should cover. In our approach, we deliberately went beyond a narrow interpretation that limits PSQA to plan verification alone.

The QA characteristics defined here are independently of any specific hard- or software and irrespective of current technical feasibility. We considered potential error sources during treatment planning and delivery, while acknowledging the relevance of error severity and occurrence as discussed elsewhere [19,20]. Nevertheless, plan verification remains an essential component of PSQA. For the specific requirements of SRT, the suitability of the verification tools must be considered. Thus, we also included the inherent capabilities of verification tools, referred to as equipment characteristics. Finally, the list of requirements was supplemented by time requirements and workflow complexity, covering setup, throughput, required machine and staff time, and the degree of automation.

We grouped these QA characteristics into the following five categories:

- Treatment planning system characteristics, consisting of:
  - o Beam modeling
  - o Dose-calculation algorithm
- Radiation machine characteristics, consisting of:
  - o Data transfer and plan deliverability
  - o Beam generation and collimation system
  - o Treatment table positioning
- Patient positioning and motion monitoring, consisting of:
  - o Patient setup and target-volume positioning
  - o Patient anatomy variations and target motion
- Equipment characteristics, consisting of:

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Table 1
Measurement QA: Hardware. (a) Type, (b) Optional phantom/material (c) Pre-treatment/in-vivo measurement, (d) Detector arrangement, (e) Dimension of single detector (width × length × height), (f) Detector spacing (center-to-center), (g) Number of single detectors, (h) Min. field size, (i) Max. measurement area, (j) Correction of beam incident angle effects, (k) Range of photon energy. (As of: January 2024)

Product/ Year of Release	IBA myQA SRS 2021	PTW Octavius 1600 SRS 2020	Scandidos Delta4 Phantom+ 2015	Sun Nuclear. SRS MapCheck 2018	Elekta/DOSIsoft XRD 1642 AP25 2015	Varian TrueBeam MV Imager 2014	Standard Imaging Adaptivo 2014	Sun Nuclear SunCheck Patient 2014
Detector Type	(a) 2D CMOS array.	(a) 2D array of liquid filled ionization chambers.	(a) Perpendicular 2D diode arrays.	(a) 2D diode array.	(a) 2D a-Si array.	(a) 2D a-Si array.	(a) Varian onboard EPID.	(a) Onboard EPID.
	(b) For rotational deliveries cylindrical RW3 phantom.	(b) Slab phantom or Octavius 4D.	(b) None.	(b) Cylindrical phantom for rotational deliveries.	(b) None.	(b) None.	(b) None.	(b) None.
	(c) Pre-treatment.	(c) Pre-treatment.	(c) Pre-treatment.	(c) Pre-treatment.	(c) Pre-treatment and in-vivo (software dependent).	(c) Pre-treatment and in-vivo (constancy check).	(c) Pre-treatment and in-vivo.	(c) Pre-treatment.
Physical Properties	(d) 2D grid.	(d) 2D grid.	(d) Two orthogonal 2D grids.	(d) 2D grid.	(d) 2D grid.	(d) 2D grid.	(d) 2D grid.	(d) 2D grid.
	(e) 0.4 mm × 0.4 mm × 0.75 mm	(e) 2.5 mm × 2.5 mm × 0.5 mm.	(e) Disc shaped, diameter 1 mm, thickness 0.04 mm.	(e) 0.48 mm × 0.48 mm	(e) Not stated.	(e) 0.336 mm × 0.336 mm.	(e)-(i) See Varian MV imager.	(e)-(k) See Elekta/ Varian EPID.
	(f) 0.4 mm.	(f) 2.5 mm central area (6.5x6.5 cm^2),	(f) 5 mm (central area 6x6 cm^2)/ 10 mm (outer area).	(f) 2.47 mm.	(f) 0.4 mm.	(f) 0.336 mm.	(k) Varian as1000 (40x30) panel: 6 MV (FFF), 10 MV (FFF), 15 MV, 16 MV, 18 MV, 23 MV; Varian as1200 (40x40) panel: 6 MV (FFF), 10 MV (FFF), 18 MV.	
	(g) 300 × 350.	5 mm outer area.	(g) 1962.	(g) 1013.	(g) 1024 × 1024.	(g) 1280 × 1280.		
	(h) 0.04 cm × 0.04 cm.	(g) 1521.	(h) Not stated.	(h) 0.5 cm × 0.5 cm.	(h) Not stated.	(h) 0 cm × 0 cm jaws and static MLC, 0.05 cm × 0.0 cm dyn. MLC.		
	(i) 12 cm × 14 cm.	(h) 1 cm × 1 cm.	(i) 20 cm × 40 cm.	(i) 7.7 cm × 7.7 cm.	(i) 40.96 cm × 40.96 cm.	(i) 40 cm × 40 cm at 100 cm SID;		
	(j) Yes, software corrected (angle sensor & look-up tables).	(i) 15 cm × 15 cm.	(j) Yes, software corrected (look-up tables).	(j) Yes, software corrected.	(j) n/a.	28 cm × 28 cm at 150 cm SID.		
	(k) 6 MV - 10 MV, incl. FFF.	(j) No, with Octavius 4D always perpendicular.	(k) 4 MV - 25 MV.	(k) 6 MV - 10 MV.	(k) 0.1 MV - 25 MV.	(j) n/a.		
		(k) Co60 - 25 MV.				(k) 4 MV - 25 MV, incl. FFF.		

Table 2
Measurement QA: Analysis Software. (a) Compatible hardware devices, (b) 2D/3D capabilities, (c) Max. dose grid resolution, (d) Interpolation, (e) Available corrections, (f) 2D/3D gamma analysis, (g) Min. distance to agreement parameter, (h) Global/local gamma analysis, (i) Definable ROI, (j) Evaluation dose threshold, (k) DVH analysis, (l) Analysis of sub-arcs/sub-fields. (As of: January 2024)

Product/Year of Release	IBA myQA Patients 2015	PTW Verisoft 2021	Scandidos Delta4 software 2015	Sun Nuclear SNC Patient 2022	Elekta/DOSIsoft (1) EPIbeam 2016 (2) EPIgray 2012	Varian Portal Dosimetry TB with aS1000, 2010; TB with aS1200, 2014; Halcyon, 2017	Standard Imaging Adaptivo 2023	Sun Nuclear SunCheck Patient PerFraction 2014
Measurement Output and Processing	(a) myQA SRS detector, MatriXX family, film.	(a) Octavius detectors, Starcheck detectors, film, DICOM, data and image files.	(a) Delta4 Phantom.	(a) MapCHECK 2+3, SRS MapCHECK, ArcCHECK devices, film.	(a) DICOM data from TPS (1,2), EPID images (1,2).	a) EPID aS1000/ aS1200, Halcyon 43x43 MV EPID,	(a) Cone Beam CT, Dynalog files, EPID images.	(a) EPID images, logfiles, CBCT data.
	(b) 2D only.	(b) 2D. Calculated 3D when using rotating Octavius 4D phantom.	(b) 2D. Calculated and measured 3D possible.	(b) 2D only.	(b) 2D (1), 3D calculated (2).	(b) 2D.	(b) 2D; calculated 3D.	(b) 2D EPID dose map; 3D calculated on planning CT or CBCT.
	(c) 0.4 mm.	(c) 1 mm.	(c) Same as CT grid.	(c) 2.47 mm.	(c) 0.4 mm (1), 0.4 mm @3-CRT, 0.8 mm - 1.6 mm @VMAT (2).	(c) 0.336 mm.	(c) 2 mm.	(c) EPID dependent.
	(d) No.	(d) Yes, for 3D dose reconstruction.	(d) Yes.	(d) No.	(d) No (1,2).	(d) Yes.	(d) No.	(d) No.
	(e) Angular and dose rate corrections, output calibration, temperature and pressure (with MatriXX only, SRS does not show T-p dependence).	(e) Cross calibration or T-p-correction recommended.	(e) Available (no details stated).	(e) Angular, field size, temperature and dose rate.	(e) sag effect (1,2), ghosting (1), nonlinearity corrections (2), a-Si-to-water correction (2).	(e) Flood field, dark field, beam profile, pixel intensity to calibration units.	(e) Not required.	(e) Image to dose conversion.
Data Analysis	(f) 2D only.	(f) 2D/3D.	(f) 3D only.	(f) 2D only.	(f) 2D only (1), 3D only (2).	(f) 2D only.	(f) 2D/3D.	(f) 2D/3D.
	(g) 0.001 mm.	(g) 0.1 mm.	(g) Available (no details stated).	(g) >0 mm.	(g) 0.1 mm (1), <10 mm (2).	(g) 0.5 mm.	(g) 1 mm.	(g) >0 mm.
	(h) Local, global and ref. dose.	(h) Local, global.	(h) Local, global.	(h) Local, global.	(h) Local, global.	(h) Local, global.	(h) Local, global.	(h) Local, global.
	(i) Yes, optional.	(i) Yes.	(i) Yes.	(i) No, full measurement area.	(i) No (1), for automatic volumes (2).	(i) Yes.	(i) Yes.	(i) No, full measurement area.
	(j) User definable.	(j) User definable.	(j) Yes.	(j) User definable.	(j) User defined protocol (1), no (2).	(j) Yes.	(j) No.	(j) User definable.
	(k) No.	(k) Yes, DICOM RT Structureset is combined with measurement.	(k) Yes. Interpolated measurement points folded with DICOM RT Structureset.	(k) No.	(k) Not applicable (1), ROI (2).	(k) No.	(k) Yes. Deformable mapping of DICOM RT Structureset to daily CBCT. Dose calculated on daily CBCT.	(k) Yes. Two modes: combination of RT images and logfiles/logfiles only. Calculated on planning CT.
	(l) Yes, field by field analysis possible.	(l) Yes, if the sub-arcs/ sub-fields were saved separately.	(l) Yes, dose is sorted into control points (sub-field or sub-arcs).	(l) No.	(l) Yes (1,2).	(l) Yes.	(l) Per beam/arc.	(l) Analysis possible for 2D gamma.

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Table 3.1
Software QA: Secondary Dose Calculation. (a) Method/algorithm, (b) Source code vendor, (c) Dose scoring, (d) Supported treatment units, (e) Commissioning data – generic model/measurement, (f) Beam modelling done by, (g) Support for beam model validation and clinical implementation, (h) Minimum field size of output factors/profiles, (i) Automatisation, (j) Data transfer error detection, (k) Evidence on software features and supported treatment modalities/techniques. (As of: August 2024).

Product / Year of Release	IBA myQA iON 2022	PTW VERIQA RT MonteCarlo 3D 2020	LAP (1) RadCalc3D 1999 (2) RadCalc3D EPID 2021	RaySearch RayStation 2009	Prosoma Core 2017	Sun Nuclear SunCheck DoseCHECK 2016	Standard Imaging IMSure 3D 2018	Elekta / DOSIsoft ThinkQA 2023	Varian Mobius 3D 2012	Radformation RadMonteCarlo 2022
Properties	(a) MC recalculation and log file analysis.	(a) MC recalculation.	(a) Modified Clarkson integration algorithm (MCIA). (1), PB (1,2), CC (1,2), MC (1).	(a) Photons: MC+CC, Ions: MC+PB, Electrons: MC. Fully equipped TPS.	(a) MC + virtual source model.	(a) CC recalculation.	(a) MC recalculation.	(a) CC recalculation.	(a) CC recalculation.	(a) Modified Finite-Size Pencil Beam (FSPB) calculation algorithm and RadMonteCarlo (RMC) recalculation + log file analysis with both FSPB and RMC.
	(b) SciMoCa (Scientific RT).	(b) SciMoCa (Scientific RT).	(b) MC: EGSnrc; MCIA, PB, CC: LAP.	(b) RaySearch.	(b) SciMoCa (Scientific RT).	(b) Sun Nuclear.	(b) SciMoCa (Scientific RT).	(b) Elekta.	(b) Mobius.	(b) Radformation
	(c) Dose-to-water or dose-to-medium.	(c) Dose-to-water or dose-to-medium.	(c) MC: dose-to-water or dose-to-medium (1), dose-to-water (2).	(c) MC Photons: dose-to-medium; CC: dose-to-water. MC electrons: dose-to-water.	(c) Dose-to-water or dose-to-medium.	(c) Dose-to-water.	(c) Dose-to-water or dose-to-medium.	(c) Dose-to-water or dose-to-medium.	(c) Dose-to-water.	(c) Dose-to-water (protons) or dose-to-medium.
	(d) C-arm linacs (MLC+Cones), Tomotherapy, Halcyon, Ethos, CyberKnife.	(d) C-arm linacs (MLC, Cones), Halcyon, Ethos, CyberKnife (MLC, Iris, Cones), Tomotherapy.	(d) C-arm linacs (1,2), Halcyon (1,2), Ethos (1,2), Cobalt (1), Tomotherapy (1), CyberKnife (MLC, Iris, Cones) (1), Gamma Knife (1), Brachytherapy (1).	(d) C-arm linacs (MLC+Cones), CyberKnife (MLC, Iris, Cones), Tomotherapy, Ion machines (PBS, US, DS, SS, Wobbling).	(d) C-arm linacs, Tomotherapy, Halcyon, Ethos.	(d) C-arm linacs with Monaco, Eclipse, Pinnacle or Raystation TPS, Halcyon, Ethos, Tomotherapy, Brachytherapy.	(d) C-arm linacs. Halcyon, Ethos, Tomotherapy, CyberKnife, ZAP-X.	(d) Elekta C-arm linacs (Agility) and Unity; not compatible with stereotactic cones.	(d) C-arm linacs, Halcyon, Ethos, Tomotherapy.	(d) Conventional Linacs, Halcyon, CyberKnife, Gamma Knife, TomoTherapy, Proton Scanning Systems, MRIdian, Unity, Superficial, Orthovoltage, Brachytherapy following TG-43, electrons following TG-71.
	(e) Generic models or custom measurements.	(e) Generic models, basic measurements.	(e) Custom measurements (except Gamma Knife).	(e) Generic models, custom measurements.	(e) C-arm linacs: generic and custom models; Halcyon + Tomotherapy: generic models.	(e) C-arm linacs: generic or custom models, measured reference needed for both; Halcyon: generic models; Tomotherapy: generic model, some measurements.	(e) Generic or custom models.	(e) Generic or custom models.	(e) Generic models, basic measurements.	(e) Generic or Custom models
	(f) Vendor (IBA employees).	(f) Vendor.	(f) User or vendor. User can replace data in generic models with measured data.	(f) Done by user after training or by vendor (as a service).	(f) Vendor.	(f) Vendor.	(f) Vendor.	(f) Model provided by the vendor; user defined beam output factors and cryostat table (Unity).	(f) Vendor. Limited parameters can be adapted by user.	(f) Vendor
	(g) Yes. Installation of the software, training and support by IBA,	(g) Yes.	(g) Yes.	(g) Yes.	(g) Yes.	(g) Yes.	(g) Yes (extra costs).	(g) Yes.	(g) Yes.	(g) Yes

(*continued on next page*)

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Table 3.1 (*continued*)

Product / Year of Release	IBA myQA iON 2022	PTW VERIQA RT MonteCarlo 3D 2020	LAP (1) RadCalc3D 1999 (2) RadCalc3D EPID 2021	RaySearch RayStation 2009	Prosoma Core 2017	Sun Nuclear SunCheck DoseCHECK 2016	Standard Imaging IMSure 3D 2018	Elekta / DOSIsoft ThinkQA 2023	Varian Mobius 3D 2012	Radformation RadMonteCarlo 2022
	clinical start supported by IBA.									
	(h) 1 cm x 1 cm.	(h) Linacs: 2 cm x 2 cm. CyberKnife: MLC 1.54 cm x 1.54 cm, Iris: 1 cm, Cone: 1 cm.	(h) User measurements not limited. Generic models: 0.5 cm (CK), 1.25 cm x 1cm (Tomo), 1 cm (Halcyon), 1.66 cm (MRIdian), 1 cm (Unity).	(h) General limit: 0.4 cm x 0.4 cm. For user measurements not limited.	(h) Profiles: 0.5 cm x 0.5 cm. OF: n/a. Only dose calibration adjustment.	(h) 0.5 cm x 0.5 cm	(h) For standard MLC: 2 cm x 2 cm, for Elekta beam modulator: 2.4 cm x 2.4 cm.	(h) 0.1 cm x 0.1 cm	(h) Not stated.	(h) User measurements not limited.
	(i) Automatic recalculation of TPS data, listening, grabbing and recalculation of logfiles, DVH calc, 3D analysis, gamma criteria evaluation.	(i) Automated evaluation, export and reporting.	(i) Import, calculation, evaluation, report generation.	(i) Open interface. Possible via scripting (CPython).	(i) Automatic calculation and report generation after data transfer via DICOM.	(i) Automatic calculation and evaluation after data transfer.	(i) Automatic import, calculation, analysis and results notification.	(i) Yes.	(i) Automatic calculation and evaluation after data transfer. CBCT, log files, and plan may be automatically transferred.	(i) No.
	(j) Yes, via logfile analysis DICOM transfer can be confirmed, and reporting missing data (e.g. RTPlan file or missing CT slice).	(j) Yes, notice when importing incomplete or incorrect data.	(j) Yes, consistency check between TPS and R&V.	(j) No.	(j) Yes, via machine logfile analysis.	(j) Transfer progress and success is indicated.	(j) Yes.	(j) No.	(j) No.	(j) No.
	(k) Yes. See vendor website.	(k) Yes. See vendor website.	(k) Yes. See vendor website.	(k) Yes. See vendor website.	(k) Yes. See vendor website or user manual.	(k) Yes. See vendor website.	(k) Yes. SciMoCa publications.	(k) No (new product).	(k) Yes. See user manual.	(k) Yes. See user manual.

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Table 3.2
Software QA: Secondary Dose Calculation. (l) Calculation of each subfield/arc/control point, (m) Min. dose grid resolution, (n) DICOM compliant dose export, (o) DVH analysis, (p) Min. distance to agreement, (q) Gamma analysis, (r) Gamma analysis using regions-of-interest, (s) Gamma analysis – dose threshold, (t) Primary/secondary dose grid adaption – interpolation. (As of: August 2024)

Product/Year of Release	IBA myQA iON 2022	PTW VERIQA RT MonteCarlo 3D2020	LAP (1) RadCalc3D 1999 (2) RadCalc3D EPID 2021	RaySearch RayStation 2009	Prosoma.Core 2017	Sun Nuclear SunCheck DoseCHECK 2016	Standard Imaging IMSure 3D 2018	Elekta/DOSIsoft ThinkQA 2023	Varian Mobius 3D 2012	Radformation RadMonteCarlo 2022
Data Processing	(l) Total plan dose and beam dose specific point in automatic mode. Field/arc dose via non-automated workflow.	(l) Composite 3D dose. Point dose per beam.	(l) No.	(l) Yes.	(l) Optional. Fields separated.	(l) Dose per field possible.	(l) Dose per field possible.	(l) No.	(l) No.	(l) Total plan dose or Dose per field.
	(m) 0.5 mm.	(m) 0.5 mm.	(m) 2 mm.	(m) 1 mm.	(m) 0.5 mm.	(m) 1 mm.	(m) 1 mm.	(m) Same as TPS dose grid resolution.	(m) 1 mm.	m) 1 mm (RMC).
	(n) Yes, via database.	(n) Yes.	(n) Yes.	(n) Yes.	(n) Yes.	(n) Yes. No direct push to TPS.	(n) Yes.	(n) Yes.	(n) No.	n) Yes (RMC).
	(o) Yes.	(o) Yes.	(o) Yes.	(o) Yes.	(o) Yes.	(o) Yes.	(o) Yes.	(o) Yes.	(o) Yes.	(o) Yes.
	(p) 1 mm.	(p) 0.1 mm.	(p) 0 mm.	(p) Possible via scripting.	(p) 1 mm.	(p) 0 mm.	(p) User defined.	(p) 1 mm.	(p) Not stated.	(p) 0.5 mm.
	(q) Local, global.	(q) Local, global.	(q) Local, global.	(q) Possible via scripting.	(q) Local, global.	(q) Local, global.	(q) Local, global.	(q) Local, global.	(q) Global.	(q) Global.
	(r) Entire patient and structure wise possible.	(r) Yes. Per default for the entire dose volume. Template-based per ROI.	(r) Yes.	(r) n/a.	(r) Global and separate analysis for OAR and target structures.	(r) Separate analysis for OAR and target structures.	(r) Yes, customizable.	(r) Automatic predefined volumes (e.g. high dose region) and ROIs from RT structure set.	(r) No.	(r) No.
	(s) Yes.	(s) Yes.	(s) Yes.	(s) Possible via scripting.	(s) Yes.	(s) Yes.	(s) Yes, customizable.	(s) Yes, customizable.	(s) Yes.	(s) Yes, customizable.
	(t) Yes. Global. Hardcoded value user definable.	(t) Yes, interpolation.	(t) Predefined dose grid (2, 3 or 5 mm).	(t) n/a.	(t) Upsampling of dose volumes to match underlying CT resolution.	(t) Dose volume is resampled to TPS dose grid size using a quadratic spline function.	(t) No. DVH template analysis comparison only.	(t) Same grid size.	(t) Voxel size can be automatically detected from TPS or can be set by user.	(t) Yes, TPS dose interpolated to match user-defined voxel size from RMC.

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Table 4
QA characteristics with potential impact on dose distribution in patients.

QA categories/ QA characteristics		Description and short discussion of its potential impact and its chance of detection by patient QA.
Treatment planning system related	**Beam modeling**	Improper beam modelling (either TPS or QA device): This could be systematic dose shifts or problems with certain classes of plans.These errors are usually not detected by a single patient plan, but by combining information of many QA runs. It is improved by independent calibration/data modelling of the QA device and a database with filter functionality for measurement results.
	Dose algorithm	Improper TPS algorithm capability regarding inhomogeneity, surface curvature, irregular fields etc. Needs re-calculation with an independent dose calculation algorithm.
Machine related	**Data transfer & plan deliverability**	Issues with the treatment plan delivery due to DICOM transfer errors or incompatibility issues between TPS and R&V system or linac, e.g. MU/degree etc. Issues may also arise due to ageing of linac components.Detection can only be achieved if the plan is fully applied before treatment (no measurement needed). Would not work for calculation-based methods or in-vivo measurements.
	Beam generation & collimation system	Machine related issues with MLC, yaws, gantry, collimator, target, beam flatness, beam symmetry, and beam quality. These could be bad MLC motors (needs high resolution dose measurement), gantry sag (identification not possible with head mounted devices, improved by angular segmented measurement evaluation), dose-monitor system (dose offset), flatness (systematic dose tilt), collimator system (field edges will not fit), beam quality (changes in lateral dose fall-off), and others.
	Table positioning	Relevant for intra-treatment table movements like in non-coplanar treatment plans or multi-isocenter treatments. Issues can be assessed by measurement with phantom/device placed on the table and measurement at planed table angles. Uncertainties in table positioning affects dose delivery precision and accuracy; no substitute for Table-Winston-Lutz-Test (machine QA).
Patient positioning/ monitoring	**Patient setup**	Patient setup uncertainties can be determined by positioning the phantom/device on the table and aligning it using the same clinical methods (laser and image guidance) as for treatment. Individual patient setup uncertainties are usually made visible using image guidance.
	Patient anatomy variations and target motion	Detection of poor immobility (e.g. masks), patient movement during treatment, changes in breathing patterns and changes or movement of anatomy require immediate observation and adequate imaging.
Equipment characteristics	**Measurement area**	Amount of measurement area covering the irradiated volume. Depends on the active detector area of the device and distance-to-source. Can be reduced by non-perpendicular incident beams.
	Absolute dose	Accuracy of absolute dose determination. Needs calibration or application of correction factors. Measurement in phantom material or water will increase this ability (scatter).
	3D dose	Capability to determine the full 3D dose-grid with adequate resolution and not just discrete planes or points. Particularly important for large and highly modulated fields and multiple metastases irradiation (off-isocenter PTVs).
	Dose gradient/resolution	Local dose discrimination capability. Should ideally be in the same range as the TPS dose-grid. Can be considered inadequate >3 mm (typical SRS PTV dose gradient regime).
Time effort/complexity		Time needed for each QA plan; machine time required for data acquisition and total staff time required for data acquisition and analysis are considered separately. Complex methods need either more time or more experience (specially trained personnel).

Table 5
Suitability of QA methods for monitoring QA characteristics (defined in Table 4). Methods marked with "4D" can potentially be used, or extended, to obtain data for gating/tracking cases.

		Treatment planning		Machine-related			Patient positioning / monitoring		Equipment characteristics				Time effort / complexity
		Beam modelling	Dose algorithm	Data transfer & plan deliverability	Beam generation & collimation system	Table positioning	Patient setup	Patient anatomy variations	Measurement area	Absolute dose	3D dose	Dose gradient/ resolution	M: Machine S: Staff
QA Methods	2D array on table at isocenter 4D	++	n/a	yes	++	0	0	n/a	large field	++	no	+	M: high S: high
	2D HiRes array on table at isocenter 4D	+++	n/a	yes	++	+	0	n/a	small field	++	no	+++	M: high S: high
	2D array on table at iso – Rotating with gantry 4D	++	n/a	yes	++	0	0	n/a	large field	++	yes	+	M: high S: high
	2D HiRes array on table at iso – Rotating w gantry 4D	+++	n/a	yes	++	+	0	n/a	small field	++	yes	+++	M: high S: high
	2D array in headmount	++	n/a	yes	++	n/a	n/a	n/a	large field	++	yes	+	M: high S: high
	EPID	+	n/a	yes	+	n/a	n/a	n/a	full field	+	yes	+++	M: medium S: medium
	EPID in vivo patient transmission 4D	n/a	n/a	no	n/a	0	+	+	large field	+	yes	++	M: n/a S: medium
	Film QA on table 4D	+++	n/a	yes	++	++	0	n/a	small field	++	no	+++	M: high S: very high
	Gel QA on table 4D	+++	n/a	yes	++	++	0	n/a	small field	++	yes	+++	M: high S: very high
	Head-mounted transition chamber	0	n/a	yes	0	n/a	n/a	n/a	full field	0	no	n/a	M: n/a S: low
	Single Point Measurement 4D	+	n/a	yes	0	n/a	n/a	n/a	n/a	+++	no	n/a	M: high S: medium
	Plan re-calculation based on CT / CBCT 4D	CT: ++ CBCT: n/a	CT: +++ CBCT: n/a	CT: no CBCT: no	CT: n/a CBCT: n/a	CT: n/a CBCT: n/a	CT: n/a CBCT: 0	CT: n/a CBCT: +++	CT: full field CBCT: large field	CT: n/a CBCT: n/a	CT: yes CBCT: yes	CT: +++ CBCT: +++	M: n/a S: low
	Log-file analysis	n/a	++	yes, if applied pre-treatment	++	n/a	n/a	n/a	full field	n/a	yes	n/a	M: n/a S: low
	In-room imaging	n/a	n/a	no	n/a	+++ (if applied for all table positions)	+++	depending on modality	n/a	n/a	no	n/a	M: n/a S: medium
	Surface-related devices (e.g. Motion Management)	n/a	n/a	no	n/a	+	++	+	n/a	n/a	no	n/a	M: n/a S: low

n/a	not applicable / no influence
0	influence present, not isolatable
+	qualitative insight
++	quantitative insight
+++	quantitative insight, highly suited
4D	Can be extended for gating/tracking capability

- Measurement area (coverage)
- Absolute dose verification
- 3D dose capabilities
- Dose-gradient and spatial resolution

- Time effort and workflow complexity characteristics

2.5.1. Summary

We present a concise set of twelve QA characteristics throughout treatment planning and -delivery that affect the dose accuracy in SRT (Table 4). These encompass physical and technical considerations. Furthermore, they provide a compact basis to evaluate and benchmark QA methods by their coverage and sensitivity to these factors.

2.6. Deriving a new approach from existing standards: comparative evaluation of PSQA methods

In conclusion of this work, we benchmarked the suitability of PSQA methods concerning the QA characteristics described in Section 2.5. This was done in a vendor-neutral manner, considering inherent capabilities rather than product-specific features (Table 5).

Detector arrays, EPIDs, and independent secondary dose calculation are most common in clinical practice for dose verification (Section 2.2) and formed the core of our vendor survey (Sections 2.3 and 2.4). To enable a comprehensive classification of PSQA methods, we considered a broader scope for this benchmarking including radiochromic film, gel dosimetry, head-mounted transmission chambers, and point-dose ionization chambers for pre-treatment dose measurements as well as log file-based dose reconstruction and tools for patient positioning and monitoring. The relevance of patient positioning and monitoring devices in this regard will be discussed further below.

The validation of treatments of moving targets using gating or tracking techniques requires dedicated approaches, e.g., with additional motion platforms or dedicated motion phantoms. Compatible methods have been marked accordingly in Table 5. Supplementary QA on dynamic phantom concepts capturing target motion (e.g., respiration) has been reviewed and will be discussed in a forthcoming publication [47].

2.6.1. Assumptions and notes

Detector arrays vary widely in spatial resolution; in Table 5 we therefore distinguish low- versus high-resolution systems. Here, low-resolution systems reflect ionization-chamber-based IMRT/IMAT solutions (detector spacing above 5 mm). High resolution systems account for dedicated SRT and more specifically SRS devices. Most pre-treatment measurements (e.g., detector arrays, radiochromic film, gel-dosimetry) are performed in homogeneous phantoms. Table 5 was compiled under these homogeneous-phantom conditions, which may not capture the complexity of heterogeneous patient anatomy. EPID is the only dose-verification tool considered both pre-treatment and in vivo. The head-mounted transmission chamber is considered exclusively for pre-treatment measurements. The rating for log file analysis presupposes a comprehensive evaluation, including independent dose recalculation and direct validation of the TPS dose algorithm.

2.6.2. Rating

We rated the suitability of each tool for each QA characteristic using an ordinal scale (+ to +++). These ratings reflect potential capabilities of QA methods within the assumptions summarized above. They resulted from extensive discussion among the authors and external experts and represent our best judgment at the time of writing (as of Dec. 2025). Because implementations and clinical workflows vary and technology evolves, readers should adapt the matrix to their own equipment and practice. Table 5 is intended as a practical guide and toolkit for selecting PSQA strategies tailored to specific error sources. It can also reveal gaps in existing PSQA programs and indicate where supplementary tools are needed.

2.6.3. Context and limitations of our findings

When employing Table 5 and conceptualizing potential PSQA scenarios, the following considerations must be kept in mind:

Pre-treatment vs. in-vivo scope: Detector arrays and film are limited to pre-treatment use, whereas EPID [16] and log file methods can be applied both before and during treatment. For stereotactic treatments, pre-treatment plan verification is commonly performed, given that large doses are often delivered in few or even a single fraction. In vivo measurements do not replace pre-treatment plan verification; if used alone, feedback arrives after delivery and may be too late to prevent errors but may provide additional retrospective feedback for subsequent fractions and future cases.

Homogeneous-phantom measurements vs. independent dose recalculation: Most plan verifications rely on measurements in homogeneous phantoms, meaning that dose accuracy in heterogeneous tissues is not tested. Ideally, heterogeneity effects should be verified either by performing independent dose recalculation on the patient's CT dataset or measurements in a dedicated heterogeneous phantom [48]. Independent recalculation accounts for tissue heterogeneities but remains algorithm-dependent and configuration-sensitive, whereas phantom measurements provide an algorithm-independent check of TPS dose, yet miss patient-specific anatomy and are limited by detector resolution and setup uncertainties.

Spatial resolution trade-off: High-resolution arrays allow to measure steep dose gradients but generally cover only small fields; low-resolution arrays provide larger coverage at the cost of gradient fidelity. In comparison with conventional IMRT/IMAT, stereotactic plans, which are characterized by small target volumes and very steep dose gradients, impose stricter requirements on spatial resolution.

Imaging methods and monitoring: Accurate dose delivery requires accurate patient positioning. Accordingly, patient imaging and monitoring is a crucial component of PSQA, especially in SRT. The QA methods listed in Table 5 for patient positioning and monitoring (in-room imaging and surface-guided systems) provide information on setup accuracy, inter- and intrafraction anatomical changes, and target motion.

Non-coplanar treatments and multi-isocenter workflows add further complexity. Planned table movements are often omitted during plan verification, either to save time or because of limitations of the measurement devices. Nevertheless, in order to reflect clinical delivery, reduce systematic errors, check for collision risks and increase sensitivity to table-angle errors, planned table movements should be considered during PSQA whenever feasible.

2.6.4. Summary

In consolidation of our findings, Table 5 serves as a structured framework for evaluating the benefit of solitaire and combined PSQA methods. It shows how verification approaches vary in their capabilities to detect potential error sources and helps to find best combinations of methods to provide an optimized error range coverage. Rather than presenting absolute or vendor-specific ratings, Table 5 was compiled to the best of our knowledge and is intended to serve as an adaptable toolkit that can be tailored to individual clinical environments, available technology, and institutional QA priorities. Users are encouraged to adjust the classification to their own conditions and experience.

The evaluation demonstrates that no single PSQA method provides comprehensive coverage of all relevant QA characteristics. Effective patient-specific QA requires a combination of complementary methods. Imaging-based verification and positioning systems contribute significantly to addressing geometrical uncertainties, while pre-treatment and log file-based methods ensure dosimetric accuracy. Machine QA and PSQA together form a coherent framework: while machine QA confirms deterministic hardware performance, PSQA validates treatment delivery under realistic, clinically representative conditions. In practice, the boundary between them is fluid; expanding PSQA may justify reducing the scope or frequency of selected machine-QA tasks, and vice versa.

The presented framework highlights both the complexity and the potential of PSQA. By combining complementary verification methods, clinics can design QA programs that are both efficient and comprehensive, ultimately improving the reliability and treatment outcomes and reducing side effects of stereotactic radiotherapy.

2.7. Expert review

A total of 74 experts in the field of stereotactic radiotherapy were invited to review our findings. The experts were located at 61 sites in Germany, Austria and Switzerland and included primarily medical physicists, but also radiation oncologists. 48 participated in a presentation of preliminary findings by the authors and 12 provided written feedback (see Acknowledgments). All responses were discussed jointly between the experts and the authors, and agreed changes were subsequently incorporated into the results. Additionally, preliminary results were presented at the joint DGMP/DEGRO symposium 2025 on stereotactic radiotherapy in Leipzig (Germany), attended by more than 250 participants.

3. Conclusion

SRT combines small fields, steep dose gradients, and tight margins. The increased usage of modulated techniques in this regime, depending on the treatment machine used, undoubtedly creates an urgent need for PSQA. Consequently, there are extremely high technological requirements for determining the 3D dose distribution delivered by the radiation systems.

3.1. Current status of PSQA in SRT

Although stereotactic radiotherapy has been established over decades and is used frequently, there is still a lack of consolidated guidelines and requirements for related PSQA. In the absence of these, a survey (see Section 2.2) revealed that users tend to find individual solutions based on their needs, equipment, and capabilities. These are mostly based on standard IMRT/IMAT PSQA protocols, using mainly gamma analysis for QA result evaluation, with partially adapted DTA-, DD- and pass/fail criteria.

The efficient and reliable verification of a high-resolution 3D dose distribution in clinical routine is still an unsolved problem. Even though approaches using plan recalculation, thus solving parts of these problems, are increasingly used. The development of meaningful evaluation metrics beyond the scope of gamma analysis together with upcoming software tools and novel detectors constitutes a significant area for future research.

Given the substantial variation in treatment devices, techniques, patient cohorts, and treatment sites, the requirements for appropriate PSQA differ markedly. This heterogeneity makes it particularly challenging to establish a linear guideline covering all potential scenarios. Consequently, users bear a high degree of personal responsibility in selecting and applying suitable PSQA methods.

3.2. Assessment of technological feasibility

Within this diverse landscape, we investigated the capabilities of current devices and technologies through vendor surveys. These surveys were conducted for active measurement devices, analysis software, and secondary dose-calculation software. To account for a holistic treatment verification process, we extended the classic approach of plan-QA, usually assessed by the aforementioned devices, to PSQA as defined in Section 2.5. We identified QA characteristics that PSQA could be considered to encompass. Subsequently, we conducted a systematic evaluation and correlation of the requirements, derived from these characteristics, with the available technologies in a vendor-neutral manner.

As a result of our findings, we presented a matrix that enables the selection of PSQA methods according to the specific needs and capabilities of a clinic.

3.3. Key results

There is no single PSQA method that covers all error sources. A practical and holistic PSQA program should combine different QA methods. Especially secondary calculation and IGRT methods have proven their value to increase patient safety and treatment outcome [49]. The patient cohort and the individual condition of each patient can influence the decision on whether and what scope of verification is needed.

Analysis methods should be selected carefully. The commonly used gamma method cannot serve as a stand-alone PSQA metric, but rather as an indicator. A future goal could be to supplement existing PSQA by verifying well-established SRT indices, such as conformity and gradient index, which is challenging with today's capabilities. Absolute dose should be verified in the regions where it is clinically relevant.

Special attention is required for gating and tracking techniques. With current technology, it is unlikely that all PSQA aspects can be fully assessed in 4D. Consequently, comprehensive machine QA remains essential to ensure the highest possible treatment quality—and, ultimately, patient safety.

CRediT authorship contribution statement

H. Gottschlag: Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing, Visualization, Validation. **B. Bathen:** Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **E. Beckers:** Data curation, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **T. Gauer:** Conceptualization, Data curation, Investigation, Methodology, Supervision, Validation, Visualization, Writing – review & editing. **D. Schmitt:** Conceptualization, Data curation, Methodology, Supervision, Validation, Writing – review & editing. **O. Blanck:** Conceptualization, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: H. Gottschlag, B. Bathen, E. Beckers and T. Gauer declare that they have no competing interests. D. Schmitt is Board Member of the Working Group for Physics and Technology in Stereotactic Radiotherapy of the German Society of Medical Physics (DGMP), Member of the Consulting Editorial Board of Z Med Phys. and was Board Member of the German Society of Radiation Oncology (DEGRO) and DGMP. O. Blanck is Board Member of the Working Group Radiosurgery and Stereotactic Radiotherapy of DEGRO and Board Member of the Working Group Stereotactic Radiotherapy of DGMP.

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Appendix A. Supplementary data

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