SGSMP
SSRPM
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Quality assurance of systems for Stereotactic Ablative Radiation Therapy (SABR)

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Contents

Preamble

This recommendation summarizes the principles of stereotactic ablative radiation therapy (SABR) and provides recommendations for the medical physicist for its implementation. SABR includes stereotactic irradiation in both cranial and extra-cranial regions of the body. It incorporates both single-fraction irradiations (stereotactic radiosurgery, SRS) and fractionated dose applications (stereotactic radiotherapy, SRT, or stereotactic body radiotherapy, SBRT) with Co-60 gamma radiation or megavolt photon radiation.

The recommendation is directed primarily to medical physicists and radiation oncologists, neurosurgeons, neuroradiologists, and radiologists, as well as to operators of therapy facilities (therapy radiographers, RTTs). It is also addressed to authorities and bodies responsible for assessing the implementation of SABR in hospitals.

This recommendation defines the minimum requirements for setting up a SABR program in the clinic and terms of equipment needed for quality assurance (QA). The recommendation is intended to promote consistent practice for SABR among radiotherapy centers in Switzerland.

The structure of this recommendation mainly follows the links of the chain of uncertainties **(see Figure 1)**.

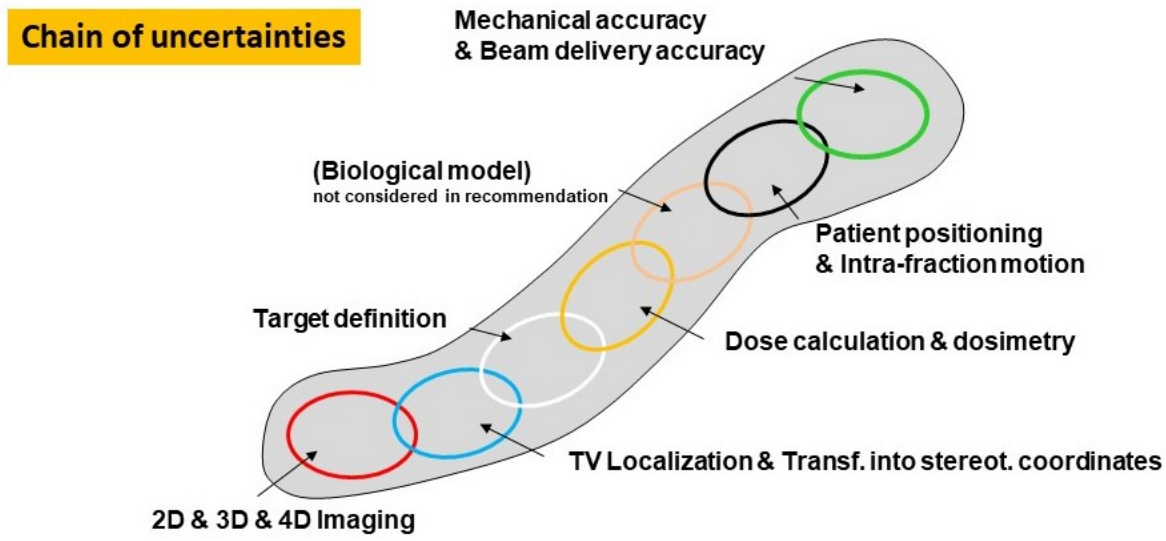

Figure1. Process Chain and associated uncertainties

1 Introduction

Radiosurgery is surgery using radiation, that is, the destruction of precisely selected areas of tissue using ionizing radiation rather than excision with a blade. Like other forms of radiation therapy, it is usually used to treat cancer, but it can also be used to treat non-cancerous lesions and functional abnormalities. Radiosurgery was originally defined by the Swedish neurosurgeon Lars Leksell as "a single high dose fraction of radiation, stereotactically directed to an intracranial region of interest." In **stereotactic radiosurgery** (**SRS**), the word "stereotactic" refers to a three-dimensional coordinate system that enables accurate

correlation of a virtual target seen in the patient's diagnostic images with the device coordinate system.

The localization accuracy and precision that is implicit in the word "stereotactic" remain of utmost importance for radiosurgical interventions.

The original concept of radiosurgery, giving the full ablative treatment dose within one session to a small target volume (typically < 15 cm^3), has now expanded to include treatments using stereotactic localization techniques to deliver small, highly conformal radiation fields in a few high-dose fractions (SRT or SBRT). Radiosurgery typically refers to a distinct neurosurgical discipline that uses externally generated ionizing radiation to inactivate or eradicate defined targets within the cranium or spine in a single fraction, without the need for a surgical incision. In contrast, SBRT is referring to none-neurological targets where the ablative treatment dose is given in one or multiple fractions and sometimes to larger volumes (> 15 cm^3). Irrespective of the similarities between SRS and conventionally fractionated radiotherapy (RT), the intent of the two approaches are fundamentally different.

The field of stereotactic fractionated radiotherapy has evolved from the original concept of SRS by applying the principles of radiobiology: repair, redistribution, repopulation, reoxygenation, and radiosensitivity. Today, both treatment techniques are complementary, as tumors that may be resistant to stereotactic fractionated radiotherapy may respond well to radiosurgery, and tumors that are too large or too close to critical organs for safe radiosurgery may be suitable candidates for stereotactic fractionated radiotherapy.

The treatment requires the interdisciplinary cooperation of physicians of various specialties (neurosurgery, radiotherapy, neuroradiology, and radiology) with medical physicists and technicians. The risk of applying significantly higher doses compared to conventional curative RT in a restricted number of fractions, the particular more sophisticated requirements for imaging (spatial accuracy), irradiation planning and irradiation devices, patient immobilization and positioning, require special knowledge and experience for all the involved personnel.

SABR requires improved delivery precision compared to conventional 3D treatment delivery. Higher confidence in targeting accuracy, facilitated by imaging and positioning techniques, is necessary to reduce uncertainties and corresponding target margins. Methods to either limit or compensate for the movement of the patient/tumor during treatment delivery are vital (for example, breathing motion). Motion management techniques include 4D computed tomography (CT), breath-hold techniques, fluoroscopy, optical surface imaging, ultrasound, electromagnetic transponders (Calypso™), and similar techniques for assessing tumor motion. Patient-related motion management techniques on the treatment machine include breath-hold and motion dampening with abdominal compression. Delivery techniques to compensate for motion include beam gating and tumor tracking. All variants have in common the requirement for dose delivery with high spatial accuracy and the steepest possible dose gradient between the target volume and surrounding tissue.

1.1 Stereotactic Fixation

Stereotactic treatments are characterized by the use of a stereotactic coordinate system, which has a fixed relationship to the patient through external localization and positioning systems. For intracranial treatments, this reference is achieved either by an invasive fixation of a stereotactic frame to the patient's skull or by the use of repositioning mask systems allowing minimal movement in addition to the use of image-based positioning. For extra-cranial treatments, immobilization may involve the use of devices such as a thermoplastic mold or mask, a vacuum mold, a bit block, or immobilization cushions.

1.2 Pre-Treatment Imaging CT/MR/PET/Angio

The following pre-treatment imaging modalities are used alone or in combination, depending on the indication. For each imaging modality, high geometrical resolution imaging is mandatory for SRS and SBRT.

CT is necessary since it is still the gold standard for geometrical accuracy. CT values (in HU) are required and are converted into electron and mass densities for use by dose calculation algorithms to accurately model tissue inhomogeneities (for details, see 3.5.1).
MRI is important because of its superior anatomical resolution (soft tissue contrast) as well as its capability to image functional properties of tissue, especially when using a scanner with high magnetic field strength. However, one must consider artifacts and distortions which must be evaluated and, if necessary, compensated for. Note: so-called MR-only workflows must be checked for geometrical distortions.
PET imaging is useful for the evaluation of active tumor areas. PET images are most often acquired in combination with CT or MRI and can be matched or co-registered with existing data sets.
Digital Subtraction Angiography (DSA) is used to define the nidus when irradiating arteriovenous malformations (AVM). 2D/3D data sets (DICOM) can be registered with the other imaging modalities in a suitable planning system.

1.3 Transformation of stereotactic coordinates/Rigid registration/Deformable image registration

Depending on the treatment device used, imaging modalities might be transformed to or equipped with stereotactic coordinates, which are used to define and distinguish the lesion to be treated.
If the images are taken with a stereotactic frame with attached fiducial boxes/rods, additional information can be found in the images (markers) and used to define a 3D stereotactic coordinate system. This transformation must be verified.
If imaging data sets (CT, MRI, PET, etc.) are registered (rigid or deformable registration), then these algorithms have to be tested [1]. Whenever AVMs are to be treated, it should be possible to import DSA images to the treatment planning system.

1.4 Definition of volumes

For SABR, similar to conventional radiation therapy, the volumes (target volumes (TV) and organs at risk (OAR)) to be considered for treatment prescription, planning, and dose reporting are defined in Report 91 by the International Commission on Radiation Units and Measurements [2].

1.5 Dose planning

Both forward planning as well as inverse planning techniques are used for SABR. In forward planning, it is typical to generate plans with several coplanar and/or non-coplanar static fields where each field aperture is shaped to the target volume either with the aid of an add-on collimator or with a multileaf collimator (MLC). In inverse planning techniques, the plan optimizer generates the optimal sequence of leaf positions. Furthermore, in volumetric arc therapy (VMAT) approaches, the plan objectives are realized by changing a combination of parameters such as MLC leaf positions, leaf speed, dose rate, and gantry speed.
For cranial SRT and SRS using special add-on collimating devices, such as cones, dose calculation methods based on factor-based or pencil kernel-based approaches have been considered sufficiently accurate, provided of course, that the dosimetric parameters (PDDs, output factors, etc.…) used by these methods are correctly determined. For SABR treatments planned and delivered using MLC and involving tissue heterogeneities, modeling the applied photon fluence and the dose in the patient necessitates the use of more complex approaches. Suitable dose calculation methods include point kernel-based superposition, Monte Carlo-based methods, or deterministic solutions to the radiation transport problem. A comprehensive review of modern treatment planning algorithms can be found in ICRU reports 83 [3] and 91 [2].

1.6 Patient Positioning/Tracking

In SABR, tighter tolerances compared to conventional RT are required for correct and stable patient positioning. If neither stereotactic frames nor masks are used, the position of the tumor

or relevant regions of the body may be tracked during treatment to guarantee a reproducible and stable position that corresponds to the one used for treatment planning and dose calculation.

1.7 Dose delivery

A requirement for treatment devices for SABR is the availability of beams at dose rates typically higher than 6 Gy/min in order to facilitate the treatment of high dose per fraction within reasonable delivery times. Appropriate collimating devices include conically drilled cones or other specialized collimations such as the Iris system on the Cyberknife machine or MLCs with leaf widths less than or equal to 5mm in order to enable the delivery of narrow beams and dose profiles with narrow penumbras, sharp dose fall-off, and low out-of-field dose. The following SABR delivery devices are well documented.

1.7.1 Leksell Gamma Knife

The Leksell Gamma Knife is a fully integrated stereotactic system with fewer degrees of freedom than a linear accelerator or the CyberKnife. With respect to machine-specific requirements, the Gamma Knife, therefore, needs more integral QA tests rather than mechanical component-based tests. Some years ago, the Gamma Knife manufacturer (Elekta Instruments AB, Stockholm, Sweden) introduced two new models - Perfexion and Icon. These models are different in design in such a way that they no longer have a separate automatic positioning system (APS), and instead, the patient positioning is integrated into the table design. Also, the trunnion mode no longer exists for these models, and the helmets (secondary collimator system) are integrated into the device in such a way that the sources move from one collimator section to the other.

1.7.2 CyberKnife

The CyberKnife (CK) Systems (VSI and M6) consists of a Manipulator (equipped with different collimator systems (cones, IRIS Collimator, MLC), a couch system, and a stereoscopic X-ray system to verify the position of the lesion. All components are attached to a common fixpoint around which the manipulator moves in 3 different SADs (650, 800, and 1000 mm). Different tracking systems allow the correct positioning of the patient (skull, spine, fiducial, and the target itself). Moving targets can be tracked by following previously embedded markers or the target/lesion itself (if visible). Most QA procedures are performed by analyzing E2E-Tests (End to End) and daily AQA (Automatic Quality Assurance).

1.7.3 Linac

Linac-based SABR has gained importance due to the continuous improvement of all the relevant components, including mechanical accuracy, imaging accuracy, cones, and small MLCs, etc.

1.7.4 Tomotherapy

This is a radiation therapy modality in which the patient is scanned across a modulated strip-beam so that only one "slice" ("tomo-") of the target is exposed at any one time by the linear accelerator beam. The system is based on helical dose delivery. The gantry rotates at a constant speed while the table moves linearly during the irradiation. The ratio of the gantry rotation speed to the table advance defines the pitch, which is smaller for a SABR than one for a non-SABR Tomotherapy delivery. It allows the system to pass at the same position more than once with only a small shift in the longitudinal direction. Additionally, the system is equipped with an MLC with leaves able to open or close in 20 ms. With this configuration, the intensity of the beam can be highly modulated, with large degrees of freedom for the delivery of dose in the TV and concomitant lowering of the dose to OARs. The system may operate with a 1, 2.5, or 5 cm longitudinal field width. The choice of the longitudinal field width depends on the expected dose distribution quality and the desired delivery time. For the precise operation of the helical mode, a mechanical accuracy of 1% of the field width on the system is necessary (this also applies to regular non-stereotactic treatments). For stereotactic irradiation

of small target volumes, the 1 cm longitudinal field width is preferred, which gives a maximum spatial tolerance of 0.1 mm.

1.8 Quality assurance

For the safe delivery of stereotactic treatments, it is imperative that strict quality assurance measures are in place throughout the radiotherapy chain. For imaging and treatment delivery units, the QA program must follow national and international recommendations [4-10]. Machine tolerances for SABR (SRT/SRS/SBRT) are generally tighter than those for modulated radiotherapy deliveries. For example, the alignment of treatment and imaging isocentres on the linear accelerator would need to be within 1 mm as opposed to the requirement of 2 mm for non-stereotactic use.

The delivery of high doses per fraction in fewer fractions and typically in small target volumes also imposes different requirements on QA carried out on individual patient's plans. Patient-specific quality assurance (PSQA) typically involves at least an independent calculation of the treatment plan and a measurement of the planed dose as delivered on suitable phantoms and detector systems. Tolerances in PSQA for SABR need to be appropriately defined. Unlike conventional radiotherapy, differences in dose values greater than 3-5% may be permissible, but positional differences in dose more than 1 mm are usually not acceptable [11].

Similar to conventional radiotherapy treatments, any commissioning of a SABR program in the clinic needs to be verified through end-to-end (E2E) testing (see chapter 2.8). This involves checking all the steps leading to the delivery, starting from imaging for the planning CT to treatment delivery and comparison of the delivered dose to the planned dose.

2 Recommendations and Technical Requirements for SABR

2.1 Patient Immobilization Systems

The stereotactic framework defines the stereotactic coordinate system. The stereotactic framework is fixed either invasively on the patient's skull, non-invasively using an individual mask (facial masks, bite block, etc.), or, in the case of SBRT, by using patient positioning devices together with image-guided positioning. Masks are generally used for fractionated treatments since an identical invasive refixation of the frame on the patient is not possible without additional devices. For single high-dose irradiations - especially for the treatment of functional disease - the invasive fixation is an option. An alternative is a non-invasive fixation combined with IGRT protocols. The stereotactic frame must have enough mechanical stability with respect to the forces and torques resulting from the fixing system. Masks must allow stable and reproducible positioning throughout the entire treatment period. Stereotactic frames and fixation must allow artifact-free imaging (CT and/or MRI).

Safety aspects: A rapid transfer of the patient (for example, from the supine position to a lateral position) must be possible in emergencies. MR compatibility must be checked when using MRI. When an invasive fixation system is used, it is usually in combination with the use of a stereotactic localizer. The stereotactic localizer should be dimensioned in such a way as to be as large as possible on all the images that are used to define the target volume without substantially increasing the field of view. The mapping of the locator itself must be artifact-free, and the images should be distortion-free or distortion-corrected. The transformation between image coordinates and stereotactic coordinates must be determinable from the geometry of the landmarks. In general, at least five landmarks per image are required for cross-sectional imaging and at least five landmarks for projection radiography. More accurate and reliable are redundant systems, e.g., nine landmarks can be used to calibrate a sectional image or eight landmarks to reconstruct a projection geometry.

If optical guided scanning techniques are used, it should be clear that in some cases, the surface moves differently than the lesion to be treated. Therefore, a correlation model has to be established. The treatment position should be comfortable enough for the patient to hold still for the entire duration of the treatment procedure.

2.2 Imaging systems for the representation of the target volume, organs at risk, and for the generation of planning imaging data

A procedure to account for inherent organ motion for targets that are significantly influenced by such motion must be established. This may include a variety of methods, including respiratory gating, tumor tracking, organ motion dampening, or patient-directed methods. The use of 4DCT in addition to a planning CT dataset may be useful in defining the motion extent of TVs and OARs. Both high 3-D spatial accuracy and tissue contrast are important imaging features for SABR.
The accuracy of the coordinate determination must be assessed by using the "known target point method," where the determined target points using clinically applied imaging methods are compared to the known target points of the phantom used [12].
The max distance between the known and measured points in the intracranial stereotactic working range must be less than 1 mm in CT and less than 1 mm in MRI in the phantom.
To define the TV and delineate OARs, for some indications, digital subtraction angiography (DSA), PET, and/or other functional imaging techniques are also required. All necessary image data must be registered with the stereotactic planning data. DSA and PET are not suitable as the sole planning data. The distance between the known and measured points in the entire stereotactic DSA working space must be, on average smaller than 1 mm.

It is recommended to select the slice orientation perpendicular to the longitudinal axis of the patient in all 3D imaging methods (MRI, CT, PET). When using CT and MRI, it must be ensured that a coherent image data set with a constant slice thickness is available in the direction perpendicular to the slice without spacing. Ideally, the isotropic geometric resolution of 3D imaging data sets should not exceed 1 mm. For SRS, a slice thickness and in-plane pixel size of less than 1 mm is recommended. Artifact-free imaging in the region of the target volume or target point is to be ensured. The acquired image data set for planning must include the total irradiated volume.
The data transfer between the imaging modalities and the therapy planning system is to be carried out using the DICOM standard.

Remarks:
To date, CT image data sets have been regarded as having the highest geometric accuracy (least distortion). Helical scanning and multi-slice acquisition methods may be preferable to axial scanning
MRI data sets show partly pronounced, nonlinear geometrical distortions in the range of several millimeters, which are dependent on the device used, the field strength, and the imaging sequence applied, as well as on the patient. Closer to the isocenter, the distortions are rather low. There are mainly two types of effects to be considered:
In the case of an inhomogeneous principal magnetic field (B_0) and gradient fields, the Larmor frequencies may lead to shifts and distortions. In the case of different constitutions of tissues, e.g., fat/water, there will be an offset of these two different tissues, visible at the boundaries.
Distortion corrections should be "switched on."
Geometrical accuracy should be evaluated with dedicated phantoms, even if distortion correction is activated.
Since patient-dependent artifacts and image distortions can't be quantified by means of phantom measurements, the determination and minimization of geometric distortions in the MR are important. Suitable image acquisition sequences should be determined and used.

The use of image intensifiers in DSA can result in nonlinear image distortions (e.g., pillow distortions) in the range of several millimeters. These effects can be eliminated by using flat-panel detectors. Otherwise, the extent of the geometric distortion must be determined by

means of a suitable lattice phantom and corrected if necessary. Alternatively, the image acquisition FOV can be suitably selected. Three-dimensional PET data sets have lower spatial resolution compared to CT and MR data sets. Pronounced geometric distortions do not occur with PET. PET images are generally integrated into the planning workflow as PET-CT or by image registration.

2.3 Requirements on transforming imaging into stereotactic coordinates/Rigid registration/Deformable image registration

Rigid registrations are affine transformations of a 3D data set, whereas deformable registrations are characterized by nonlinear mapping of voxels.
There are different ways of transforming different imaging modalities into stereotactic coordinates:

a) Using a stereotactic frame
   When using stereotactic frames, different localizer systems are used to provide additional information during the scans. This information – seen on the images – is transformed into stereotactic coordinates during the definition process in the planning system. During treatment, these coordinates must be adjusted at the treatment device to position the target point relative to the isocenter or unit center point UCP.
b) Anatomical fusing & matching [1]
   If no frame is used, then the necessary imaging modalities must be matched to the CT, which is the reference dataset for the planning process. Since the additional datasets are scaled and overlaid, not all regions will fit perfectly. A qualified person must check the correctness of the registration. Note: MR-only workflows (which generate a pseudo-CT based on MRI) can give acceptable electron/physical density and dose calculation results [13]. However, in certain body regions, patient-related artifacts and distortions are not compensated.
   Calculated DRRs, which are generated by the treatment planning process to predict the position of the target within the patient, must be verified by live images during treatment. Alternatively, a (Cone Beam) CT is acquired in the treatment position prior to treatment and registered to the planning CT.
c) Anatomical registration and matching, including deformable algorithms
   Whenever deformable image registration algorithms are used, the scaling is not linear anymore, meaning that extra QA is mandatory to evaluate these algorithms [1]. A qualified person must check the correctness for each patient and registration.

2.4 Requirements on defining target volumes and organs at risk

For guidance on the definition and outlining of target volumes and organs at risk, it is recommended to follow the guidance provided in the report by the ICRU report 91 [2].

2.5 Requirements for treatment planning systems

2.5.1 Imaging

The treatment planning system (TPS) must be able to import data from different imaging modalities (e.g., MRI, PET) and to allow image correlation and registration between these. The possibility to correlate these image data sets with subsequently collected image data during and after treatment (follow-up) is strongly recommended. The integration of DSA should be possible in the treatment of AVMs.

2.5.2 Dose calculation and accuracy requirement

Patient images from CT are preferred for the calculation of the dose. As treatment plans for SABR originate from a sum of doses from many small fields (either static or part of a modulated field comprising from a summation of small fields shaped by an MLC), the requirement on the TPS is that its fluence and dose calculation methods account for changes from reference irradiation conditions both in irradiation geometry and the irradiated medium. The TPS needs

to model source size effects (occlusion of the finite photon source by the collimating device) and the influence of the collimating device itself; in the case of an MLC, this involves the shape of the MLC leaf ends and the transmission and leakage between leaves. This is because, in SABR plans, the MLCs leaves not only affect the shape of the penumbra but also influence the dose in the target volume. Lateral electron transport and changes due to density variations in the patient become important primarily at high megavolt beams and in low-density media [2]. These modeling challenges are addressed differently by different commercial TPSs, and performance on accuracy is subject to implementation. For this reason, it is recommended to use a TPS that incorporates models that address these effects and to configure and verify these carefully.

The TPS is required to include models to account for radiation originating or scattered from the head of the linear accelerator as well as source size effects and the influence of collimating devices and models to accurately calculate dose in heterogeneous media. A discussion of the use of various algorithms can be found in [32].
The smallest permissible collimator setting to be used for dose calculations on the TPS must be limited to the smallest setting for which dose can be accurately determined by measurement, and this obviously relates to the size of the detector available for measurement. The choice of field size also depends on the alignment of isocenters of the treatment machine (mechanical, radiation, and imaging) and the suitability of the image data and the planning system (voxel size, basic data). Field sizes of ≤ 5 mm, based on the 50% isodose in the isocenter, are typically used for functional radiosurgery.

It is thus strongly recommended to follow international guidance on good practice for the acquisition of dosimetric data [14-18]. See the paragraph below on the determination of dosimetric data in small photon fields. It is also strongly recommended to follow TPS manufacturer instructions on the data requirements for the configuration of TPS models.

The resolution in dose calculation for treatment planning needs to be set to at least the voxel size used for imaging. If this is not possible, for SRS, a dose grid voxel size of less than or equal to 1 mm and for SBRT of less than or equal to 2 mm (depending on target size) is recommended. For the calculation of intracranial targets, all slices must be able to be used from below the target to the superior part of the skull.

2.5.3 Plan normalization

Traditionally in SRS, doses were prescribed to a percentage dose level of 50% to 80%, covering the planning target volume (PTV) with the maximum of 100% within the PTV. Analogous to this, nowadays, prescriptions for SABR typically specify that 100% of the prescribed dose (the 100% dose level) covers almost 100% of the target volume allowing an escalation of dose within the target volume to between 125% and 200% of the prescribed dose.

2.5.4 Plan evaluation tools

The planning system must offer the visualization of the 3D dose distribution and at least the representation of isodose lines in orthogonal planes. Furthermore, the calculation of dose-volume histograms is a necessity, and this includes the calculation of plan statistics such as the near-minimum and near-maximum dose in the target volume and in the OARs. It is also desirable to obtain other plan quality metrics such as the conformity index, homogeneity index, gradient index, coverage, etc. [2], [19]. The input and output of coordinate values must be possible in the stereotactic system.

2.5.5 Determination of dosimetric data in small photon fields

The reference medium for dosimetry is liquid water. The determination of dosimetric data (scanned line doses and dose ratios) in small photon fields is not straightforward. There are detector dependencies related to their size and direction with respect to the radiation beam and due to their composition in relation to water. Non-water-equivalent detectors cause perturbations of the particle fluence in the irradiated medium, and this leads to under- or over-

estimation of the dose, and for this reason, their readings need to be appropriately corrected. In addition, care is needed during measurement to ensure that detectors are correctly positioned within the small field. Guidance of good practice in terms of choice of detectors, measurement methodologies, and correction factors needed to correct for detector-related dependencies are provided in reference [18]. It is strongly recommended to follow this guide for the determination of dosimetric parameters in small fields. The table below provides a general overview of the main detector types available for dosimetry in small photon fields in the clinic, classified according to their suitability in terms of size, energy independence, water-equivalence, signal-to-noise ratio, and signal linearity.

2.5.6 Import and Export

The interfaces of the TPS for the import and export of the data used must be disclosed and documented by the manufacturer. Preferably, the DICOM-RT standard is to be used. A plan summation, e.g., in the case of a post-irradiation, is desirable, as is the possibility to create, load, and edit standard plans for quality assurance. The planning system should allow the calculation and the graphical and numerical output of any dose profiles, those of line and surface profiles, possibly also the output of the entire dose matrix. This also allows the transfer of dose calculations from therapy plans to phantoms for dose verification. Plan parameters need to be available for use by external dose or MU calculations systems.

	Spatial Resolution	Energy Independence	Water-equivalence	Signal to Noise Ratio	Signal Linearity
Small volume ionization chamber	-	+	-	+	++
Stereotactic Diode	+	0	-	+	+
Synthetic micro Diamond detector	+	+	-	0	+
TLD	+	0	+	+	0
Radiochromic Films	++	+	++	0	0
Organic scintillation detector	++	++	++	0	+

Table 1: Overview of detectors available for dosimetric measurement in small photon fields: ++: very suitable, +: suitable, 0 neutral, -: not suitable without correction

2.6 Requirements for patient positioning (TV and OARs) & image-guided treatment delivery

Patient setup uncertainty is a significant contribution to the treatment chain of uncertainties and therefore has to be kept as low as reasonably achievable. Due to the generally small volumes of the targets, the small applied margins (if given), and the high dose gradients, stereotactic treatments must strive for the highest technically achievable setup accuracy and reproducibility. Upper tolerance limits on the setup accuracy and reproducibility, which generally should be in the order of 1-2 mm, are determined by (a) the margins added to the CTV to get the PTV and to the OAR, if any, (b) the dose gradient(s) and (c) the proximity of and/or the constraints on any OARs. Note: the mentioned contributions a-c are not independent of each other.
Single fraction SABR treatments with doses higher than typically 4 Gy [20] require special attention regarding patient immobilization systems and should be completed with image guidance at least prior to and at selected time points during the beam delivery. Real-time monitoring of the target or surrogate with real-time 6 degrees of freedom correction of the patient support or the beam delivery system during delivery is highly desirable, thus compensating possible translational *and* rotational shifts of the patient or the tumor.

X-ray imaging techniques during beam delivery consist of 2D kV and/or MV images, DTS images (Digital Tomosynthesis), and 3D images such as short arc CBCT. It is highly recommended to use the imaging options clinically available on the treatment delivery device to acquire X-ray images during treatment, ensuring accurate target positioning either by visual inspection of some related surrogates or fiducial markers or by using feature/fiducial marker detection tools to automatically detect a potential target and/or patient motion during beam delivery. The applied imaging dose must be documented.

For targets subject to respiratory motion, one or several of the following motion management strategies should be used: (a) motion encompassing methods based on 4D-CT imaging, employing ITV concepts or the like, (b) breath-hold, (c) forced shallow-breathing, (d) respiratory-gating or (e) respiration-synchronized free-breathing tracking techniques (f) abdominal compression. Which of these strategies are to be used is determined by the clinical goal, the anatomical situation/constraints, the capabilities of the patient, and the available techniques onsite.

In the case of gating or tracking techniques (d) and (e), usually active (e.g., LEDs) or passive (e.g., reflective IR markers), stereoscopic optical tracking systems or video photogrammetry are used to continuously track the 3D coordinates of selected points on the outer contour of the patient or the surface as a whole assuming a correlation of the vertical movement of the optical markers with the movement of the target or internal markers in 3D space. In some systems, stereo-optical technology is used to monitor and control the movement of the patient support during the application of translational and/or rotational corrections of the patient setup.

2.7 Requirements for the treatment device and dose delivery

Medical linear accelerators that are used to deliver stereotactic treatments should provide photon beams with energies between 4 and 10 MV. Lower photon energies lead to unfavorably low depth dose values in the target volume, and higher energies lead to a decrease of the lateral dose gradient because of the increased range of secondary electrons.

The Gamma Knife (Co-60 device), with a mean energy of 1.25 MeV, is only used for intracranial applications, for which this energy is sufficient. To be able to apply high single doses more quickly and thus shorten the treatment time during therapy, dose rates of up to 10 Gy/min and even higher are common.

The radius of the isocenter sphere must be less than or on the order of 1 mm to achieve the required positional accuracy of the irradiation. At the time of accelerator installation, attention must be paid to the mechanical alignment of all rotation axes and the radiation isocenter, the quality of which essentially determines the accuracy of the treatment. The patient support and

positioning system must have temporal stability under load (up to 135 kg) with a maximum drift of 1 mm/hour [21]. With the table motor brakes activated, the translational play of the patient support must be less than 1 mm.

2.7.1 MLC

For the conformal irradiation of small target volumes (<15 cm^3) in the brain, field sizes should be adjustable with an accuracy of 0.5 mm (at the isocenter). When using MLC, the projected width of the leaves at the isocenter should be 5 mm or less. In addition, the reproducible setting accuracy of all translations and rotations, especially in the case of dynamic irradiations, is important. In particular, the combination of gantry rotation and the dynamic field-shaping by the MLC leaf motion must be reproducible with variable dose rates and different gantry rotation speeds. Mechanical stability of all components is the prerequisite for an exact dose application. In the special case of treating functional disorders using an MLC, the projected width of the leaves at the isocenter for these field sizes should be $\leq$3 mm.

2.7.2 Cones/Collimators

Add-on circular cone collimators must be securely, reproducibly, and stably mountable to the linac or gantry head. Fine adjustment of the add-on collimators must be possible in order to minimize the rotational wobble of the collimator rotation axis and reduce the size of the radiation isocenter sphere. The individual add-on circular cone collimators must be coded and under the control of the linac record and verify (R&V) system to prevent the omission or use of a wrong-sized cone.

2.7.3 IRIS Collimator

Field-size quality assurance of a variable, approximately circular, aperture collimator is necessary and can be performed by means of dose-area product measurements [22]. The use of this collimator is only recommended for field sizes > 10 mm in diameter.

2.8 Quality assurance – (overall accuracy – system test, E2E tests)

Modern SRS and RT delivery devices can achieve geometrical and dose localization accuracy on the order of 1 mm, which is clinically necessary, but only when comprehensive and rigorous QA is applied.

End to End (E2E) testing of the treatment workflow is an important step to evaluate the accuracy of the overall treatment process, which is usually not tested by recommended tests of the sub-component. It is known that the E2E or system tests that are part of treatment credentialing processes often demonstrate a significant, if not unacceptably high, failure rate, even when quite relaxed acceptance thresholds are applied [23].

An E2E test can be defined as follows: A test which uses a phantom containing a hidden target and film (orthogonal films) or any other 2D dose measurement device running along the clinical workflow from simulation (planning CT/MR) to segmentation and registration, dose planning and dose calculation, phantom setup and positioning (using available IGRT technology) and treatment. Typically, an E2E or system test shall cover the geometrical positioning accuracy (Winston-Lutz type test) and the dosimetric dose localization and absolute dose accuracy for single targets with a single isocenter and for multiple targets/multiple isocenters or single isocenter if these treatments are to be applied. The E2E test can be executed on a static or moving phantom and for a single fraction (SRS) or multiple fraction (SRT/SBRT) stereotactic treatments. The phantom should be usable together with stereotactic frames if these are used clinically.

The results from plan-specific QA (PSQA) in modulated radiotherapy are usually compared against a reference dose matrix (measurement or independent calculation) using the gamma index analysis [24], [15]. The gamma index is a measure combining dose difference and the difference in a location receiving the same dose (distance-to-agreement, DTA) using user-defined tolerance criteria. The report by AAPM TG Report No. 218 [11] provides a comprehensive discussion on the appropriate choice of criteria for the calculation of the gamma index. For plan comparisons in homogenous media and in non-SABR planning, the gamma index is typically evaluated using the tolerance criteria of 2 % difference in the dose

and 2 mm difference in DTA [11]. In the specific case of SABR and, in particular, SRS, where the positional accuracy of the applied dose is of importance, the tolerance criteria are of the order of 5-7% in dose difference and less than 2 mm in DTA. To test the dose localization accuracy, the measured 2D dose distributions are matched with the calculated ones to determine the offset required. This test can be applied for moving targets also. It is obvious that this E2E or system test is NOT considering any clinical uncertainty in tissue delineation and definition. These uncertainties are usually addressed separately.

E2E or system tests are recommended by a variety of recommendations. [7] recommends such a test but does not provide a tolerance threshold. [10] also recommends such a test and gives a threshold of 0.95 mm for static and 1.5 mm for moving phantoms. The test is based on geometry and dose localization (70% isodose line), and it is recommended that it be done monthly. [25] gives a threshold of 2.0 mm. The DIN 6875-2 [26] does not mention a threshold in mm but gives a test frequency of 6 months and includes the dose localization accuracy (50% isodose line). The 2016 ACR-ASTRO recommendation [27] on the performance of brain stereotactic radiosurgery has a geometrical accuracy requirement of 1 mm.

3 Tests and Tolerances

3.1 Frames/masks/immobilization

For **frame-based stereotactic treatments**, fiducials are rigidly attached to non-deformable objects (frames) that can be reliably registered to the target.
Frameless stereotactic treatments use either surrogate anatomies such as bone (constituting a volumetric fiducial) which is well established in relation to the target, or uses the target itself (e.g., identified on the image guidance system) or fiducials that are registered immediately before or during the targeting procedure. These immobilization devices should undergo visual inspection regularly.

3.2 Imaging devices

The following modalities are available for imaging: CT, MRI, DSA, and PET. Appropriate imaging protocols that will depend on the indication must be established for optimum visualization of the target volume and the organs at risk in the stereotactic coordinate system. Procedures should ensure that changes and service interventions on imaging systems are reported to the responsible medical physicist so that they can carry out unscheduled constancy tests if necessary.
For all image modalities, the image data and its transfer (DICOM, CD, etc.) to the therapy planning system must be tested for integrity and consistency.

3.2.1 CT

The following imaging protocol parameters shall be defined:

- Slice thickness and pixel size
- Scan-FOV such that the localizers can be detected
- Scan mode (slice mode, spiral mode, number of slices used in multi-slice CT)
- Parameters that determine the contrast and noise

The following tests are recommended:

- Test the specific patient support or fixation on the CT table for the attachment of the stereotactic frame or mask system for mechanical fit and stability.
- Determine the mean accuracy and standard deviation of stereotactic target points in the entire stereotactic space by using a suitable phantom, e.g., known target point phantom for clinically used imaging protocols [28].

The following shall be documented:

- Documentation of all clinically used imaging protocols and specification of average target point accuracy and standard deviation.
- Documentation of all parameters and imaging protocols, including the breathing curve when using 4D-CT.
- Documentation of test results.

Remarks:
CT gantry tilt and CT table sag can affect stereotactic target point accuracy. It has to be ensured that there is no gantry tilt chosen and that table sag is taken into account when testing the accuracy by putting some weight on the table.

3.2.2 MRI

The following imaging protocol parameters shall be defined:

- Slice thickness and pixel size
- Parameters that determine resolution, contrast, image noise, artifacts, and image distortion. In this case, image artifacts caused by, for example, eddy currents and the invasive fixing of the stereotactic frame must be considered.
- When using MRI with a stereotactic localizer:
  Scan-FOV such that the localizers can be detected

The following tests are recommended:

- When using MRI with stereotactic localizer:
  - Test the specific patient support or fixation on the MR table for the support of the stereotactic frame or mask system.
  - When using MRI with a stereotactic localizer, the mean localization accuracy of stereotactic target points and their standard deviation in the entire stereotactic space must be determined by using a known target point phantom for clinically used imaging protocols
- Determine image distortions with a suitable phantom, e.g., "Known Target Phantoms," and, if necessary, minimize them, for example, by selecting appropriate imaging parameters or by referring to the manufacturer's instructions.

The following shall be documented:

- Documentation of all clinically used protocols for which the geometrical integrity has been verified.
- Documentation of test results.

Remarks:

- Verify MRI compatibility and safety of the used equipment and instruments.
- Ensure that the vendor-provided distortion correction is activated (most modern MRI scanners are equipped with this feature).
- Increase the acquisition band width (BW) as much as imaging demands allow (FOV, SNR). Thus, chemical shifts, susceptibility artifacts, and metal artifacts can be reduced.
- The geometrical integrity should be within DSV (diameter spherical view).
- Don't solely rely on echo-planar imaging (EPI) sequences for geometrically critical contouring purposes. If not avoidable, consider the acquisition of additional patient-specific distortion information (e.g., distortion field maps) and/or the use of easily implementable distortion correction methods (e.g., gradient-reversal techniques).
- Be aware of the direct linear relationship between the magnitude of geometrical distortion artifacts (chemical shift, susceptibility) and magnetic field strength.
- As the magnetic field strength increases, the stereotactic accuracy of the target point can decrease because of local patient-dependent susceptibility artifacts.
- Image distortions should be primarily minimized by the image acquisition system/protocol and not only minimized by deformable image registration techniques involving the CT.

3.2.3 PET

The following imaging protocol parameter shall be defined:

- Slice thickness and pixel size.
- Scan-FOV such that the localizers can be detected.
- Scan mode (static or dynamic).
- Duration of the PET scan, number of bed frames.
- Injected activity (MBq) and patient mass (kg).
- Reconstruction parameters: ordered-subset expectation maximization (OSEM), Time of Flight (TOF), Point spread function (PSF).
- Reconstruction parameters: number of iterations/subsets, post-filter smoothing.
- Reconstruction parameters: z-axis filter, all corrections that apply.
- CT attenuation correction parameters: kV, mAs, pitch, slice thickness.

The following tests are recommended:

- NEMA [29] image quality test performed four times a year (quarterly) that yields the resolution, contrast, and small lesion detectability.
- Geometrical calibration and localizer check four times a year (quarterly). Specification of average target point accuracy and standard deviation.

The following shall be documented:

- Documentation of all clinically used imaging protocols and specification of average target point accuracy and standard deviation.
- Documentation of test results.

3.2.4 Digital Subtraction Angiography (DSA)

The following imaging protocol parameters shall be defined:

- Beam orientation
- Field size such that the localizers are visible also after image subtraction
- Parameters that determine the contrast and noise

The following tests are recommended:

- Test the specific patient support or fixation on the DSA table for the attachment of the stereotactic frame or mask system for mechanical fit and stability.
- In the case of an image intensifier-supported system, the image distortion must be determined, documented, and, if necessary, corrected using a lattice phantom. The measurement must be carried out in the same geometry as the patient measurements.
- Determine the mean localization accuracy of stereotactic target points and their standard deviation in the entire stereotactic space by using a known target point phantom for clinically used imaging protocols [27].

The following shall be documented:

- Documentation of all clinically used imaging protocols and specification of average target point accuracy and standard deviation.
- Documentation of test results.

3.3 Transfer of stereotactic data/Rigid registration/Deformable image registration

Check the input devices for functionality and accuracy of the planning system(s) for all relevant medical imaging data (CT, MRI, PET, DSA). Assure correct anatomical registration: left-right, anterior-posterior, cranial-caudal from all the appropriate input devices.

If the imaging is performed without stereotactic localization (e.g., MRI, PET), it must be ensured that appropriate registration methods are available to maintain a localization accuracy of 1.5 mm (image registration).

For deformable image registration, it is recommended to check the deformation vector field and the resultant anatomy as it is known that deformable image registration algorithms could lead to non-physiologic deformations [30], [1]

3.4 Definition of Targets and OARs

Follows the approach described in [2].

3.5. Planning Systems

For the testing of treatment planning systems, see [31]. For specific SABR related topics, the recommendations and procedures of the treatment planning system manufacturer must be followed.

3.5.1 Algorithms

An independent check on the dose distribution and/or monitor units is a requirement in Switzerland, and in addition to this, PSQA with a dose measurement is recommended. As part of the periodic QA representative set of plans can be defined, calculated, and measured at regular time intervals.

3.6 Patient adjustment and motion assessment

Whenever patient adjustment or target motion assessment systems is used the following aspects have to be considered.

3.6.1 Patient adjustment systems

Whenever patient adjustment systems are available, the following options are common in clinical use.

3.6.1.1 Skull

The bony anatomy of the skull is used as a reference for tracking. DRRs are usually used as a reference and compared to X-ray images acquired in real-time. Differences in the skull position between the DRR and the X-ray are calculated and corrected for.

3.6.1.2 Spine

Usually, the spine is moving during treatment. Modern spine tracking methods need no rigid image registration but accurately track the movements of the targets directly by comparing pre-calculated DRRs with live images (e.g., with a mesh). The measured deviations are adjusted and corrected by the treatment device.

3.6.2 Motion assessment

Motion assessment is the process whereby the actual time-dependent 3-D displacements of the target or a reliable surrogate are quantified. Motion assessment is typically performed with 4D CT but can also be performed with real-time fluoroscopy or other time-dependent imaging technologies. The quantified time-dependent motion trajectory for the specific patient's tumor is considered in the context of the planning processes, techniques, and constraints, with specific consideration for the method of motion control that is to be used. For example, treatment planning using an ITV/PTV expansion approach may require the motion envelope to be very similar in size to the target volume (i.e., very little motion) to avoid unacceptable toxicity after delivery of ablative dose levels. In contrast, tumors that can be effectively tracked or gated may be allowed to have a considerably larger motion envelope. In either case, the target displacements over time should be monitored.

3.6.2.1 Marker-based

Since most soft tissues contain no structures that can be used for tracking based on X-ray imaging, radiographic landmarks "fiducials" or RF beacons are implanted on the perimeter of or in the target and used as a reference for tracking. Currently, two types of markers exist:

implanted fiducial markers, which are localized with the help of imaging (e.g., CT, X-ray), and those who are localized without imaging using a different detection technology (Calypso™ System). Relative translations and rotations between the patient position at planning and during treatment can be detected and corrected for. If at least three markers are used, both translations and rotations can be considered. This method monitors tumor positions throughout the treatment by establishing a path of motion in near real-time based on the motion pattern of the tissue where the markers are embedded. It ideally synchronizes the treatment delivery to the motion of the tumor itself throughout the treatment.

3.6.2.2 Without marker

This method does not use fiducial markers for tracking lesions within the lung during treatment but instead directly uses the target itself. The use of this method requires that the target can always be detected by imaging methods.

3.6.2.3 Motion correlation

The motion is controlled by either an optical system which must be correlated with the tumor or marker movement, or by X-rays which detect the actual positions of the markers. The time interval between taking the stereoscopic X-ray images must be defined by a qualified person.

3.6.2.4 External surrogate

If an external surrogate for motion assessment is used, such as an optical marker based system, typically used for beam gating, the surrogate must achieve a spatial accuracy of ≤ 1mm/≤ 0.5°.

3.7 Treatment devices and dose delivery

3.7.1 Gamma Knife

3.7.1.1 Machine Interlocks

The Gamma Knife is equipped with several machine interlocks. Door interlocks, emergency switches, radiation lights, etc. which should be tested on a regular basis, equivalent to the recommendations for linear accelerators. Other Gamma Knife-specific interlocks, such as patient arm rest interlocks, should also be tested on a regular basis and at least once per year.

3.7.1.2 Collision Tests

In practice, it is possible to plan treatment positions in such a way that the patient's head, or the fixation frame, collides with the helmet. Possible collisions that may cause a problem are recognized by the planning system. These coordinates should be checked prior to treatment.

3.7.1.3 Helmet Tests

For each helmet, a safety check is required. The helmet ID is recognized by the console by means of micro switches. The switch should be inactivated at 0.1 mm shim, indicated by a red LED on the test box. According to the manufacturer, this test should be performed weekly.

3.7.1.4 Radiation Safety Tests

Since a Gamma Knife uses permanent Co-60 radiation sources, an independent radiation alarm should also be operational when no patients are being treated. Regular wipe-tests, radiation surveys, and radiation leakage tests should be performed. The frequencies for these tests are prescribed by the legislation controlling office.

3.7.1.5 Patient Positioning

The patient should be positioned relative to the "isocenter" (Unit Center Point, UCP) of the sources of the Gamma Knife with sub-millimeter accuracy.

3.7.1.6 Automatic Positioning System (APS)

The automatic system can be checked by simply reading the rulers on the APS. The accuracy of the system is specified to be <0.2 mm. Left and right APS have separate motors.

Inconsistencies between left and right positions can be detected by the system itself.

3.7.1.7 Trunnions

A meaningful test can be performed by simply checking if the left and right coordinates are the same when the patient is mounted. This can be done for every patient that has trunnion coordinates. Also, trunnions can be checked by comparing them to a slide ruler. This is only advised in case of suspected deformation.

3.7.1.8 Patient Positioning System (PPS)

In the Gamma Knife Perfexion/Icon models, the helmet and positioning systems are integrated into one patient positioning system. The overall accuracy of this system should be within 0.3 mm.

3.7.2 CyberKnife

3.7.2.1 Manipulator/Robot

The positions on the virtual sphere around the overall fix point (nodes) are checked on a yearly basis by the manufacturer "Robo-Mastering." The correctness of this calibration is indirectly checked by various tests.

3.7.2.2 Couch

There are two different couch systems available, a pedestal couch (6 degrees of freedom) and a Robo-Couch 6 or 7 degrees of freedom (with the 7th degree, you can pick up a patient from a wheelchair by a "seated load" option). Although all corrections during the treatment are compensated for by the manipulator, both couch systems should be checked for correct orientation.

3.7.2.3 X-ray System

The X-ray System is mounted on the ceiling – X-rays (images) are captured by detectors in the floor. The geometry is at 45° to the horizontal plane. The geometry of the stereoscopic imaging system is crucial and is checked regularly by the manufacturer and checked on a daily basis by the user (see AQA test, Table 2).

3.7.2.4 Connection of all coordinate systems

All treatment components (Manipulator, Couch, and X-ray System) are connected to one fixed point. This point can be simulated by a reference point to which all components can be adjusted and is checked by the manufacturer once a year. The accurate adjustment is tested by E2E tests by the user (see Table 2).

3.7.2.5 Touch Guard Systems

Manipulator and couch systems are equipped with touch guard systems to be checked daily by touching them.

3.7.3 Linac

3.7.3.1 Linac and Couch

Stereotactic treatments are precision irradiations of small target volumes that require increased geometric accuracy compared to conventional irradiations. The commissioning of a linear accelerator for stereotactic irradiations must fulfill the following requirements and comprise the following activities:

- Ensure the required accuracy of the beam collimation and beam guidance system considering the rotation axes of the gantry, table, and gantry head (diameter of the "stereotactic isocenter sphere").
- Ensure the stability of the patient positioning and the required accuracy of the positioning of the target point on the center point of the stereotactic isocenter sphere. In the case of multiple lesions being treated with a single isocenter, special care should be taken concerning positioning errors due to rotation.

3.7.3.2 Imaging

- Imaging and mechanical isocenter should be within 1 mm.

3.7.4 Tomotherapy

3.7.4.1 Linac and Gantry

For complete machine-related QA, all the additional tests, tolerances, and test intervals defined in the regulations [8] and [33] are valid and mandatory for both stereotactic and standard treatments. In particular, to accurately perform stereotactic treatment with a Tomotherapy unit, the following tests require a maximum deviation of 1 mm:

- MVCT geometric distortions dimension, orientation (described in [8] AAPM TG Report No. 148 Section VI.B.I.a)
- Image/laser coordinate coincidence (described in [8] AAPM TG Report No. 148 Section VI.B.I.b)
- Laser initialization described in [8] AAPM TG Report No. 148 Section V.B.4.b)

3.8 Delivery QA

3.8.1 Accuracy of radiation delivery

An adequate technique for treatment verification is film-dosimetry with radiochromic films [34, 35]. Other techniques, such as high-resolution detector arrays, exist. However, their spatial resolution is typically an order of magnitude lower. Verification should be done in orthogonal planes intersecting the isocenter.
Dose calculation on the verification phantom considering the correct electron densities must be done with the finest dose grid available. For Monte-Carlo dose calculation algorithms, the dose uncertainty should be appropriate. Dose planes must be exported for comparison with the film measurements. The exact positioning of the orthogonal radiochromic films relative to the linac coordinate system (e.g., the laser system or IGRT based phantom setup) is a prerequisite.
For comparison of calculated dose planes and film measurements, we recommend at least using one of the following techniques:

1) Comparison of predefined isodose lines:
   Distances of the 30%, 50%, and 80% isodoses should be estimated.
2) Comparison of profiles through the isocenter:
   Dose max values and position of 50% isodoses should be compared.
3) Comparison using the Gamma-Criterion:
   Distance to an agreement must fulfill a more stringent criterion than dose difference, e.g., a 3%/1.5 mm criterion is recommended. For field sizes below 10 mm, an increased dose difference (5-7%) is acceptable.

3.8.2 Overall Accuracy

The primary goal is to get information on how accurately the dose gradient can be positioned at a certain localization. Concerning the link imaging at the beginning of the "chain of uncertainties," a CT should be chosen, knowing that there will always be an additional offset when using different imaging modalities.

3.8.2.1 E2E Tests

Based on the geometric and dosimetric performance of today's stereotactic treatment delivery systems, the following is recommended for the E2E or system test:

- Use of an appropriate phantom with embedded structures to perform Winston-Lutz tests.
- Use of an appropriate phantom with embedded film planes to perform isodose measurements.
- Use of an appropriate phantom for frame-based and frameless SABR. The phantom should allow MR and PET imaging and registration to CT.

- Use of an appropriate phantom that can be positioned using IGRT devices and optical positioning and monitoring devices.
- Geometrical (3D) deviation of expected to measured localization
    - SRS (no motion): Threshold = 1 mm
    - SRT/SBRT (no motion): Threshold = 1.5 mm

3.8.2.2 E2E Tests including motion

- In the case of active motion compensation (CK, MLC/Couch tracking) or passive motion compensation using beam gating, only a representative regular motion pattern should be applied. Non-irregular motion is not considered. However, it is important to keep in mind that regular motion patterns are not patient representative.
- The use of an appropriate phantom - either being movable or mounted on a motion stage is recommended.
- Geometrical (3D) deviation of expected to measured localization
    - SRS (including motion): Threshold = 1.5 mm
    - SRT/SBRT (including motion): Threshold = 2.0 mm

4 Summary of tests to be performed

Recommended QA tests are summarized in **Table 2.**
These tests should also be performed after maintenance, upgrades, or the repair of the system.
Patient-specific QA may be performed by either point dose-, film- or 2D-array measurements.

Chapter	**Systems/Devices**	**Test**	**Frequency**	**Tolerance** cranial/body
3				
3.1	**Fixation by stereotactic frames**	Visual inspection	*after 50 patients or at least every 6 months*	against baseline
3.2	**Imaging devices**			
3.2.1	CT (Planning CT)	Evaluation of the geometrical integrity with a dedicated phantom (e.g., known target phantom)	*6 m*	≤ 1mm/≤1 mm
3.2.2	MR	Evaluation of the geometrical integrity with a dedicated phantom (e.g. known target phantom)	*1a*	≤ 1 mm/≤ 3 mm within DSV (diameter spherical view) ≤ 3 mm/< 5 mm (elsewhere)
3.2.3	PET	Performed by Manufacturer (NEMA)	*6 m* *3 m*	no influence here
3.2.4	Angio / DSA	Performed by Manufacturer	*6 m*	≤ 1 mm/≤1 mm
3.3	**Transfer of stereotactic data / Registration / Merging** frame-based frameless	workflow TPS QA	*1a*	against baseline (geometrical consistency)
3.5	**Planning Systems**			
	Plan Consistency	verification	*3 m*	against baseline
3.5.1	Algorithms	2nd dose check	*every patient*	

3.6	**Patient adjustment and motion assessment (incl. CBCT) ***			
3.6.1	Patient Adjustment Systems			
3.6.1.1	Skull	E2E-Test	*m*	≤ 1 mm
3.6.1.1	Spine	E2E-Test	*m*	≤ 1,5 mm
3.6.2	Motion Assessment			
3.6.2.1	Marker-based	E2E-Test	*m*	≤ 2 mm
3.6.2.2	Without marker	E2E-Test	*m*	≤ 2 mm
3.6.2.3	Motion correlation	E2E-Test	*m*	≤ 2 mm
3.6.2.4	External surrogate	Against a ground truth movement	*m*	≤ 1mm/≤ 0.5°
3.7	**Treatment device and dose delivery**			
3.7.1	Gamma Knife	UCP via System Test	*m*	≤ 1 mm
3.7.2	Robot/Manipulator (CK) comp. TG 135	*AQA Reference point*	*d*	≤ 1 mm
3.7.3	Accelerator/Linac	e.g., Winston Lutz	*d*	≤ 1 mm
3.7.4	Tomotherapy	E2E-Test or Winston Lutz	*d*	≤ 1 mm
3.8	**QA (radiation delivery)**			
3.8.1	Accuracy of radiation delivery	Planning vs. measurement comparison	*m*	≤ 1 mm/≤ 2 mm
3.8.2	Overall Accuray			
3.8.2.1	E2E (static)	System Tests	*m (alternating)*	≤ 1 mm/≤ 1.5 mm
3.8.2.2	E2E (motion management)	System Tests	*m (alternating)*	≤ 1.5 mm/≤ 2 mm

Abbreviations: Baseline (measured data are consistent with or better than the data acquired during acceptance and commissioning measurements), d: daily (when treating), w: weekly; m: monthly, a: annually.
* If E2E-Tests result in errors larger than the tolerance, it is recommended to identify the major sources of uncertainty along the chain of uncertainties.

Table 2: Overview of required tests, frequencies, and tolerances.

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