SRT and SBRT: Current practices for QA dosimetry and 3D

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Abstract. The major feature that separates stereotactic radiation therapy (cranial SRT) and stereotactic body radiation therapy (SBRT) from conventional radiation treatment is the delivery of large doses in a few fractions which results in a high biological effective dose (BED). In order to minimize the normal tissue toxicity, quality assurance of the conformation of high doses to the target and rapid fall off doses away from the target is critical. The practice of SRT and SBRT therefore requires a high-level of confidence in the accuracy of the entire treatment delivery process. In SRT and SBRT confidence in this accuracy is accomplished by the integration of modern imaging, simulation, treatment planning and delivery technologies into all phases of the treatment process: from treatment simulation and planning and continuing throughout beam delivery. In this report some of the findings of Task group 101 of the AAPM will be presented which outlines the best-practice guidelines for SBRT. The task group report includes a review of the literature to identify reported clinical findings and expected outcomes for this treatment modality. Information in this task group is provided for establishing an SBRT program, including protocols, equipment, resources, and QA procedures.

1. Introduction
Over 4000 publications spanning several decades have affirmed the clinical usefulness of stereotactic radiosurgery (SRS) in the treatment of benign and malignant lesions as well as functional disorders. The radiobiological rationale for SBRT is similar to that for SRS; delivering a few fractions of large dose in relatively short overall treatment time results in a more potent biological effect. The clinical outcomes of SBRT for both primary and metastatic diseases compare favorably with surgery with minimal adverse effects. In addition, the limited number of treatment fractions makes SBRT more convenient for the patient, and a potentially more cost-effective treatment modality than traditional radiation therapy.
For both SRS and SBRT patient-specific quality assurance is a critical component in the overall quality control of radiation treatment as it provides assurance that the delivered dose will accurately match the planned dose distribution. In particular, it is important to verify that the treatment device is physically capable of delivering the planned dose distribution and that patient setup in the treatment room matches as closely as possible the patient setup at time of simulation.

Patient-specific QA becomes even more critical for Stereotactic Body Radiation Therapy (SBRT). SBRT differs from traditional radiation therapy in that it features highly conformal, hypofractionated dose delivery. Current SBRT protocols generally involve 3-5 treatments with a dose of 6-22 Gy per fraction to
sites such as the spine, liver, and lung[3, 6, 7, 9, 10, 28, 33]. The desired biological effect is achieved both by fractionation and perhaps more importantly by the differential dose delivered to targeted and normal tissue; the goal is to minimize the volume of normal tissue exposed to a high dose of radiation. Therefore in SBRT the traditional gross tumor volume (GTV) and clinical tumor volume (CTV) as described in ICRU 62[12] are often treated interchangeably[29, 35, 36]. SBRT is also highly dependent on image guidance for localization and repositioning. The requirements of large doses and highly accurate targeting in SBRT mean that special attention needs to be paid to all aspects of the treatment for each patient, including immobilization, localization, pre-treatment dose verification and review of on-board imaging by the physician.

2. Problems associated with dosimetry of small/narrow field geometry

SRT, SBRT and IMRT routinely use small fields and beamlets of less than 10 mm in diameter in order to achieve the desired, highly-focused and precisely modulated dose distribution. Measurement of small photon beams is complicated by the loss of lateral electronic equilibrium, volume averaging, detector-interface artifacts, collimator effects, and detector position-orientation effects. Due to the small dimensions and steep dose gradients of photon beams used in SRS/SRT and IMRT, an appropriate dosimeter with a spatial resolution of approximately 1 mm or better (stereotactic detectors) is required to measure the basic dosimetry data, e.g., the total scatter factor (SF, or relative output factor), tissue-maximum ratio (TMR), and off-axis ratios (OARs). Even with stereotactic detectors, careful detector-phantom setup, and detailed dose corrections, one might still find more than 10% discrepancies among the measurements of very small fields (< 10 mm in diameter). MLC-shaped fields have more geometry and dosimetry uncertainties than those of the circular cones. Li et al. demonstrate that large errors are often caused by a small setup error or measuring point displacement from the central ray of the beam[18]. For small MLC fields, the collimator leaf-edge effect is almost independent of the depth but is closely related to the field size and type of MLC. The volume effect becomes significant when the detector diameter is comparable to the half size of the small fields.

For the profile (off-axis ratio) measurement of the small photon beams, Higgins et al. demonstrated a simple approach to unfolding the chamber size artifact from measured small-beam profiles using typical cylindrical chambers by de-convolving the detector-response artifact from each point in the profiles. The maximum inner diameter of a detector should be less than half the FWHM of the smallest beam measured in order for the deconvolution of the detector-size effect to work properly.

3. Comprehensive QA Program for SRS and SBRT

Patient-specific QA procedures for SRS/SBRT should be developed as an integrated part of a comprehensive ongoing QA program in the clinic. Therefore, before implementing an SBRT program, the clinic first needs to determine which system(s) will be used and develop QA procedures to match. SBRT-enabled systems often have specialized equipment such as immobilization systems, localization systems, and on-board imaging systems which are not always found in the clinic. In other cases, the entire system is specialized for SBRT (e.g. the Accuray Cyberknife). For example, Table 1 summarizes the stereotactic localization and image guidance strategies used by commercially-available systems. These specialized components require detailed and specialized QA procedures, over and beyond the general guidelines for external beam radiotherapy as specified in the AAPM Reports of TG 40, 142, and 45[16, 23, 15].
Table 1. Comparison of typical characteristics of 3D/IMRT radiotherapy and SBRT

| Characteristic                             | 3D/IMRT          | SBRT                 |
|-------------------------------------------|------------------|----------------------|
| Dose / Fraction                           | 1.8 – 3 Gy       | 6 – 30 Gy            |
| # Fractions                               | 10 – 30          | 1-5                  |
| Target definition                         | CTV / PTV (gross disease + clinical extension): tumor may not have a sharp boundary. | GTV / CTV / ITV / PTV (well-defined tumors: GTV=CTV) |
| Margin                                    | Centimeters      | Millimeters          |
| Physics / dosimetry monitoring            | Indirect         | Direct               |
| Required setup accuracy                   | TG40, TG142      | TG40, TG142          |
| Primary imaging modalities used for treatment planning | CT               | Multi-modality: CT/MR/PET-CT |
| Redundancy in geometric verification      | No               | Yes                  |
| Maintenance of high spatial targeting accuracy for the entire treatment | Moderately enforced (moderate patient position control and monitoring) | Strictly enforced (sufficient immobilization and high frequency position monitoring through integrated image guidance) |
| Need for respiratory motion management    | Moderate – must be at least considered | Highest             |
| Staff training                            | Highest          | Highest + special SBRT training |
| Technology implementation                 | Highest          | Highest              |
| Radiobiological understanding             | Moderately well understood | Poorly understood |
| Interaction with systemic therapies       | Yes              | Yes                  |

Table 2 summarizes recommendations for annual, monthly, and daily QA activities for SBRT clinics which enable verification of overall device accuracy.

Table 2. Achievable accuracies reported in the literature categorized by body site and immobilization / repositioning device

| Author / year    | Site       | Immobilization / Repositioning                                                                 | Reported accuracy |
|------------------|------------|-----------------------------------------------------------------------------------------------|-------------------|
| Lax-1994[17]     | Abdomen    | Wood frame / stereotactic coordinates on box to skin marks                                     | 3.7mm Lat         |
|                  |            |                                                                                               | 5.7mm Long        |
| Hamilton-1995[8] | Spine      | Screw fixation of spinous processes to box                                                      | 2mm               |
As an example specifically relevant to SBRT, Table 3 lists published repositioning accuracies of various SBRT immobilization schemes. The reported accuracies vary significantly depending on the particulars of the approach, however in general errors in target localization and patient repositioning can be sorted into two categories: (1) set-up errors, which can be greatly reduced with proper localization procedures and (2) organ motion, especially motion due to the respiratory cycle, which can be highly dependent on the specific geometry and respiratory characteristics of the patient. QA procedures must therefore be developed that can address repositioning errors at the device level as well as the patient level.

| Author          | Organ(s) | Device Description                                                                 | Accuracy  |
|-----------------|----------|------------------------------------------------------------------------------------|-----------|
| Murphy-1997[20] | Spine    | Frameless / Implanted fiducial markers with real time imaging and tracking          | 1.6mm radial |
| Lohr-1999[19]   | Spine    | Body cast with stereotactic coordinates                                             | ≤ 3.6mm mean vector |
| Yenice – 2003[37] | Spine  | Custom stereotactic frame and in-room CT guidance                                  | 1.5mm system accuracy, 2-3mm positioning accuracy |
| Chang-2004[2]   | Spine    | MI™ BodyFix with Stereotactic Frame / linac / CT on rails with 6D robotic couch     | 1 mm system accuracy |
| Tokuuye-1997[30]| Liver    | Prone position                                                                     | 5mm       |
| Nakagawa-2000[22] | Thoracic | MVCT on linac                                                                      | Not reported |
| Wulf-2000[34]   | Lung, Liver | Elekta™ body frame                                                                | 3.3mm lat 4.4 mm long. |
| Fuss-2004[4]    | Lung, liver | MI™ BodyFix                                                                        | Bony anatomy translation 0.4, 0.1, 1.6 mm (mean X, Y, Z); Tumor translation before image guidance 2.9, 2.5, 3.2 mm (mean X, Y, Z) |
| Herfarth-2001[10] | Liver  | Leibinger body frame                                                               | 1.8-4.4 mm |
| Nagata-2002[21] | Lung     | Elekta™ body frame                                                                 | 2mm       |
| Fukumoto-2002[3] | Lung    | Elekta™ body frame                                                                 | Not reported |
| Hara-2002[9]    | Lung     | Custom bed transferred to treatment unit after confirmatory scan                   | 2mm       |
| Hof-2003[11]    | Lung     | Leibinger body frame                                                               | 1.8 – 4 mm |
| Timmerman-2003[28] | Lung | Elekta™ body frame                                                                 | Approx. 5mm |
| Wang-2006[32]   | Lung     | Medical Intelligence Body Frame stereotactic coordinates / CT on rails              | 0.3 ± 1.8mm AP -1.8 mm±3.2mm Lat 1.5 mm ± 3.7 mm SI |

Table 3. Summary of published QA recommendations for SBRT and SBRT-related techniques.
Table 4 summarizes these two types of errors and lists strategies for verifying target localization, for both inter- and intra-fraction variations. Image guidance can often be used to correct for setup errors. However, organ motion is not as easily accommodated, and further strategies that include compensation for this motion must be employed.

**Table 4.** Types of positional errors and error management strategies for SBRT
### STRATEGY

| Immobilization/Setup Aids | Off-line | On-line |
|---------------------------|----------|---------|
| Setup Errors              |          |         |
| Inter-fraction            |          |         |
| Alignment/Constraint      | Conventional weekly port film practice | MV-Radiographs (conventional ports) |
| Standard procedures       |          |         |
| Lasers/Light Field on Tattoos | Statistical Approaches: | EPID MV-Radiographs |
| Thermoplast masks         | i) Population-based thresholds. | | |
| Tape                      | ii) Individual-based thresholds. | On-line kV Radiographs (with/without markers) | |
| Bite Blocks               |          |         |
| Vacu-Form molds/casts     | (see note a) | MV Fluoroscopic kV Fluoroscopic Optical Video Monitoring |

| Intra-fraction            |          |         |
| Thermoplast Body Casts   |          |         |
| Stereotactic Head Frame  |          |         |
| Stereotactic Body Frame  |          |         |

| Organ Motion              | Inter-fraction | Intra-fraction |
|---------------------------|----------------|---------------|
| Breath-hold Consistent Time-of-Day | Off-line strategies based on repeat CT scans. | On-line Computed Tomography (CT-on-a-rail, Cone-Beam CT, Tomotherapy) |
| Active Breathing Control  |                |               |
| Specifications (bladder/rectum, full/empty) |        | Ultrasound |
| Patient position (prone/supine) | Other imaging modalities (MRI, Ultrasound) | |

| Organ Motion              | Inter-fraction | Intra-fraction |
|---------------------------|----------------|---------------|
| Breath-hold Compression Plate | (see note a) | Respiratory Gating Cardiac Gating MV/kV Fluoroscopy of surrogates for organ motion |
| Active Breathing Control  |                |               |

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a Devices and procedures often serve not only to provide accurate inter-fraction alignment (setup aids) but also to constrain against intra-fraction motion (immobilization devices); hence, the distinction between inter- and intra-fraction strategies is blurred in this case.

b Although off-line correction strategies do not address intra-fraction variability directly, such strategies may provide margins which better accommodate such variability provided the inter- and intra-fraction motions are from the same distribution.
4. Simulation and Treatment Planning

As discussed earlier, one of the characteristics of SBRT is that treatments are simulated and planned with the goal of providing the smallest possible margins to minimize the dose to normal tissue, account for motion of the tumor, and provide a repeatable set up. A variety of techniques for accounting for tumor motion within the PTV have been described and are summarized in the report of AAPM task group 76.[14] The efficacy of many of these techniques (for instance, breath-hold techniques) can vary on a patient-specific basis and therefore require patient-specific QA procedures to verify their appropriateness in any given situation.

Treatment planning may require patient-specific quality assurance procedures to ensure the dose distribution is within the appropriate dose-volume constraints for both the target and all relevant organs at risk (OAR).

The clinic should have established procedures for a second check and patient specific QA for SBRT treatments. An axial CT slice is shown for a spinal SBRT plan in Figure 1, with the PTV contoured in red.

Figure 1. Axial CT slice for a spinal SBRT treatment showing the PTV (red contour) and isodose distribution

Figure 2 provides an example of strategies that could be applied to patient-specific pre-treatment dose verification. Figure 2a illustrates patient specific QA that was performed for the treatment in Figure 1 on the TomoTherapy® Hi-Art system® (TomoTherapy Inc.) for a spinal SBRT treatment. Film is used to determine the measured isodose curves for a single plane, which is then compared to the planar dose determined from the planning system, along with a point dose at the plane of the film and the gamma distribution. Additionally, the dose to a point (usually isocenter) is determined using an ionization chamber, which is then compared to the calculated dose at that point. An SBRT plan for the same patient was developed for delivery on a Varian Trilogy™ linear accelerator (Varian Medical Systems Inc.), with the QA performed using a MatriXX array (IBA Dosimetry GmbH). The isodose curves for a single plane for this treatment are shown in Figure 2b, along with the gamma distribution. The QA program used for
SBRT needs to be well understood by the planning team, including changes in the plan, such as scaling of the monitor units so that film is not saturated, that need to be performed for the specific QA technique.

![Image](image1.png)

**Figure 2.** QA performed for the plan in Figure 1 on the a) TomoTherapy Hi-Art and b) Varian Trilogy linear accelerators.

5. **Patient repositioning and treatment delivery**

Current SBRT systems rely on image guidance for patient repositioning at the beginning of each fraction of treatment. Typically, simulation images are transferred to the treatment console and are co-registered with kV and/or MV images acquired with the on-board imaging from the treatment device. Offsets in the resultant co-registration are detected as setup shifts required to bring the patient into optimal setup correspondence with the simulation position. The clinic should have specific quality assurance procedures to evaluate the quality of the OBI imaging as well as the quality of the final patient setup. This may include a procedure that requires the OBI be reviewed and approved by the physician for each fraction.

6. **Conclusion**
The authors have presented four tables summarizing the generalized patient specific QA issues associated with SBRT, and these include:

Table 1: Comparison of typical characteristics of 3D/IMRT radiotherapy and SBRT

Table 2: Reported accuracy of SBRT immobilization and repositioning systems.

Table 3: Summary of QA recommendations for SBRT systems

Table 4: Error-analysis strategy for set-up and organ motion.

A dosimetric analysis for a spinal SBRT is presented in two figures which demonstrates the issues that must be addressed in verification of dose planning and delivery. For further and more comprehensive discussion on patient specific QA for SBRT the readers are advised to refer to the AAPM Task Group 101.

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