FULL PAPER

Operation and calibration of the novel PTW 1600SRS detector for the verification of single isocenter stereotactic radiosurgery treatments of multiple small brain metastases

1ESTHER DECABOOTER, MSc, 1ANS CC SWINNEN, 1MICHEL C ÖLLERS, 2FABIAN GÖPFERT and 1FRANK VERHAEGEN

1Department of Radiation Oncology (Maastro clinic), GROW School for Oncology, Maastricht University Medical Centre+, Maastricht, The Netherlands

2PTW Freiburg, Freiburg, Germany

Address correspondence to: Mrs Esther Decabooter
E-mail: esther.decabooter@maastro.nl

Objectives: The aim of this work was to evaluate the operation of the 1600SRS detector and to develop a calibration procedure for verifying the dose delivered by a single isocenter stereotactic radiosurgery (SRS) treatment of small multiple brain metastases (BM).

Methods: 14 clinical treatment cases were selected with the number of BM ranging from 2 to 11. The dosimetric agreement was investigated between the calculated and the measured dose by an OCTAVIUS 1600SRS array detector in an OCTAVIUS 4D phantom equipped with dedicated SRS top. The cross-calibration procedure deviated from the manufacturer’s as it applied field sizes and dose rates corresponding to the volumetric modulated arc therapy segments in each plan.

Results: Measurements with a plan specific cross-calibration showed mean ± standard deviation (SD) agreement scores for cut-off values 50%, 80%, 95%, of 98.6 ± 1.7%, 96.5 ± 4.6%, 97.3 ± 4.4% for the 6 MV plans respectively, and 98.6 ± 1.5%, 96.6 ± 4.0% 96.4 ± 6.3%, for the 6 MV flattening filter free (FFF) plans respectively. Using the default calibration procedure instead of the plan specific calibration could lead to a combined systematic dose offset of 4.1% for our treatment plans.

Conclusion: The 1600SRS detector array with the 4D phantom offers an accurate solution to perform routine quality assurance measurements of single isocenter SRS treatments of multiple BM. This work points out the necessity of an adapted cross-calibration procedure.

Advances in knowledge: A dedicated calibration procedure enables accurate dosimetry with the 1600SRS detector for small field single isocenter SRS treatment of multiple brain metastases for a large amount of BM.

INTRODUCTION

Patients with multiple brain metastases (BM) are treated with stereotactic radiosurgery (SRS) that used high dose per fraction, and therefore require dedicated equipment, special planning techniques and small treatment margins to achieve high dose conformity.1,2 A complex linear accelerator (linac) based delivery technique to achieve high dose conformity is volumetric modulated arc therapy (VMAT) where the dose rate, the gantry rotation speed and multi-leaf collimator (MLC) aperture shape varies dynamically during the arc delivery.3 A single isocenter technique can be applied to efficiently deliver the dose while requiring less than one-half of the beam time required for multiple isocenter set-ups.4 The use of single-isocenter non-coplanar beams can further increase the conformity of the treatment plans making them competitive to Gammaknife treatment plans.5 By using a single isocenter technique, there is an increased risk of geometrical miss. Lesions located further away from the isocenter are more sensitive to rotational set-up errors.6 For this reason, frameless thermoplastic immobilization masks in combination with daily imaging-based set-up corrections, using cone beam CT (CBCT) in combination with a 6 degrees-of-freedom robotic couch and the use of optical surface tracking systems, are crucial for this irradiation technique.7,8 Planning target volume (PTV) margins down to 1 mm are appropriate assuming an adequate imaging and/or tracking system.9,10 This state-of-the-art irradiation technique for the delivery of highly conformal radiation fields to multiple BM requires efficient and accurate quality assurance (QA) measures and equipment.10 The dosimetric verification of this irradiation
technique poses several unique challenges such as the highly modulated VMAT plans containing small fields, a volumetric spread of the treatment lesions over the brain volume and treatment plans containing non-coplanar beams. The OCTAVIUS 1000SRS liquid filled 2D ionization chamber (IC) array has been described as an excellent detector for small field dosimetry especially for verifying stereotactic treatments.\textsuperscript{11,12} The array detector can be inserted in the OCTAVIUS 4D phantom with the SRS top to perform a three-dimensional (3D) verification. However, the measuring area of the 1000SRS is restricted to $11 \times 11 \text{cm}^2$, and therefore too limited for dose verification of multiple BM in the head. The advanced OCTAVIUS 1600SRS array detector has similar properties but an enlarged active detector of $15 \times 15 \text{cm}^2$ to include all BM in an extended measurement volume. This work aims to study the operation of this novel detector for a relevant number of clinical cases.

As the VMAT plans required for this irradiation technique are typically highly modulated and consist of small subfields shaped by the MLC. The recommended cross-calibration procedure may not be suitable for these treatment plans. The second aim of this work was to develop a dedicated cross-calibration procedure, using the field sizes and dose rates determined for the treatment cases.

**METHODS AND MATERIALS**

Treatment cases and delivery

Table 1 summarizes 14 clinical SRS treatment cases with number of BM ranging from 2 to 11. The fractionation schemes were determined in accordance with the Dutch guidelines depending on the volume of the largest PTV.\textsuperscript{13} Both coplanar and non-coplanar RapidArc treatments using 6 MV flattened as well as unflushed beams were considered during planning, and treatment plan calculation was done with AcurosXB algorithm v. 15.5 (Varian Medical Systems, Palo Alto, CA). A detailed description of the treatment cases and delivery techniques can be found in Supplementary Material 1. The PTWs and the distance to the isocenter are mentioned to illustrate the spatial arrangement of the BM.

Operation procedure of the detector array

The 1600SRS detector is inserted in the OCTAVIUS 4D phantom. Controlled by an inclinometer, the OCTAVIUS 4D phantom rotates synchronously with the gantry, keeping the 1600SRS detector array perpendicular to the beam while taking time- and gantry angle-resolved dose measurements.\textsuperscript{14} The measurements were performed using an OCTAVIUS 4D phantom top with a diameter of 17 cm corresponding to a source-to-surface distance (SSD) of 91.5 cm (Figure 1). The OCTAVIUS 1600SRS consists of 1521 liquid-filled IC distributed over an active measurement area of $15 \times 15 \text{cm}^2$. Each detector covers a cross-section of $2.5 \times 2.5 \text{mm}^2$ with a height of 0.5 mm, resulting in an active volume of approximately 0.003 cm$^3$. The adjacent chambers are distributed heterogeneously with a center-to-center distance of 2.5 mm in the inner area ($6.5 \times 6.5 \text{cm}^2$) and 5.0 mm in the outer area ($15 \times 15 \text{cm}^2$) (Figure 1). For each treatment plan, the measured dose was reconstructed to a 3D dose volume using the OCTAVIUS 4D dose reconstruction algorithm in VeriSoft, v. 8.0 (PTW-Freiburg, Germany).\textsuperscript{14} In the TPS, the treatment plans were projected on the artificial homogeneous phantom CT data set provided with the OCTAVIUS 4D system and recalculated. The electron density of the OCTAVIUS 4D phantom relative to water was set to 1.016 g/cm$^3$ according to the manufacturer's recommendations.

The OCTAVIUS 4D algorithm uses percentage depth dose (PDD) curves independently measured with an ionization chamber in water at a SSD of 85 cm corresponding to the SSD when using a standard top with a diameter of 32 cm. With a source to isocenter distance of 100 cm, the average SSD for the rotational unit equipped with the SRS top is 92 cm, taking the curved surface into account. Verisoft was used to create new PDD data for a SSD of 92 cm based on the PDD data for a SSD at 85 cm for different field sizes ranging from $1 \times 1 \text{cm}$ to $26 \times 26 \text{cm}^2$ defined at the isocenter. Consequently, these PDD data are used to reconstruct dose values along the ray lines that connect the relevant detectors and the focus of the beam.\textsuperscript{14} The phantom was positioned at the isocenter using the room lasers and each plan was measured separately at couch rotation zero. For treatment plans with a mixture of coplanar and non-coplanar beams, a dedicated algorithm in Verisoft was used to reconstruct the dose distribution using the actually planned couch angles. To evaluate the dosimetric agreement between the measured and calculated dose a 3D $\gamma$ evaluation method implemented in Verisoft was used with a (local) $\gamma$ criterion of 2%/2 mm and cut-off values of 50%, 80% and 95%.\textsuperscript{15} This means that voxels with doses below 50%, 80% or 95% of the maximum calculated dose were ignored in the analysis. These values were chosen to encompass most of the irradiated volume, re-evaluate the PTV coverage and focus on the higher dose regions, respectively.

Calibration procedure

To ensure a TPS-independent dose verification, the array detector was cross-calibrated with a pinpoint IC (PTW, Freiburg, Germany) (0.015 cm$^3$ volume). The dose corresponding to 100 MU (6 MV) and 500 MU (6 MV FFF) in the isocenter was measured using a PMMA insert allowing the pinpoint IC to be positioned at the isocenter within the OCTAVIUS 4D phantom. The dose measurement with the pinpoint IC was corrected with the daily output variation of the linac. A non-negligible dependence of field size and dose-rate on the response of the liquid filled ionization chamber of the 1600SRS detector is described by in literature.\textsuperscript{16} Since the treatment plans consist of small field sizes and varying dose rate, especially in the case of the 6 MV FFF treatment plans, the development of an accurate calibration procedure is necessary:The dose-per-pulse dependency of the detector and the volume effects described by Poppe et al. vary with field size and are especially pronounced for small field sizes.\textsuperscript{16} Therefore, PTW recommends to perform the cross-calibration with a field size matching the field size of the clinical plan. For small field sizes, this is typically $5 \times 5 \text{cm}^2$. As the clinical treatment plans in this study contain a lot of very small VMAT segments contributing to the dose distribution, the equivalent field sizes (EFSs) were calculated for all the 14 treatment plans using equation (1) for a rectangular field:\textsuperscript{15}

$$EFS = \frac{2 \times L \times W}{W + L}$$

(1)
Table 1. Overview of the clinical treatment plans in this study

| Plan no. | Amount of PTVs | Fractionation scheme | Treatment technique (couch angles in degrees) | PTVs (cm³) | Distances of PTV to isocenter (cm) |
|----------|----------------|----------------------|-----------------------------------------------|------------|-----------------------------------|
| 1        | 2              | 3 × 8 Gy             | Coplanar (0)                                  | 0.59/4.07  | 6.99/0.78                         |
| 2        | 3              | 3 × 8 Gy             | Coplanar (0)                                  | 19.35/9.29/2.72 | 9.32/6.84/0.08                   |
| 3        | 4              | 3 × 8 Gy             | Coplanar (0)                                  | 17.6/2/0.2  | 3.44/2.3/4.52/3.81                 |
| 4        | 4              | 3 × 8 Gy             | Coplanar (0)+Non-coplanar(270)                | 2.47/1.44/3.75/1.77 | 2.75/3.55/4.84/3.78             |
| 5        | 4              | 1 × 8 Gy             | Coplanar (0)+Non-coplanar(270/315/45/90)      | 2.47/1.44/3.75/1.77 | 2.75/3.55/4.84/3.78             |
| 6        | 4              | 1 × 24 Gy            | Coplanar (0)                                  | 1.04/0.22/0.44/0.11 | 3.21/5.64/6.96/6.16         |
| 7        | 5              | 1 × 24 Gy            | Coplanar (0)                                  | 1.62/0.14/0.2/0.1/0.13 | 5.39/4.2/5.81/4.98/4.93        |
| 8        | 6              | 3 × 8 Gy             | Coplanar (0)+Non-coplanar(270)                | 0.25/0.1/2.44/0.21/0.15/0.08 | 6.87/4.76/3.32/5.47/5.21/4.4  |
| 9        | 7              | 3 × 8 Gy             | Coplanar (0)                                  | 2.23/2.15/0.66/0.23/0.13 0.15/0.1        | 0.12/5.96/2.54/5.89/5.35/5 764.69 |
| 10       | 8              | 3 × 8 Gy             | Coplanar (0)+Non-coplanar(270)                | 9.18/3.13/1.58/1.16/0.34/0.170.32/0.12 | 4.98/5.65/5.57/4.22/5.76/3.81 5.43/6.58 |
| 11       | 8              | 3 × 8 Gy             | Coplanar (0)+Non-coplanar(270)                | 17.17/0.53/0.34/0.73/0.57/0.52/0.3/0.1  | 5.78/4.25/5.36/6.78/4.8 6.67/2.37 |
| 12       | 9              | 3 × 8 Gy             | Coplanar (0)                                  | 4.17/3.19/3.8/0.97/0.45/0.48/0.16/0.14/0.17 | 2.74/5.18/2.52/1.57/3.4/4.54/4.54/4.89/5.72 |
| 13       | 10             | 3 × 8 Gy             | Coplanar (0)                                  | 0.82/0.08/5.47/0.07/0.71/0.71/0.09/0.07/0.82 | 6.71/4.24/4.49/4.07/3.12/5.7/6.9/6.82/5.14/7.34 |
| 14       | 11             | 1 × 24 Gy            | Coplanar (0)+Non-coplanar(270)                | 0.17/0.25/0.33/0.65/0.24/0.1/0.85/0.35/0.2/0.13/0.14 | 7.18/6.26/4.82/7.88/1.8/4.99/7.3/5.42/7.32/7.68 |

PTV, planning target volume.
Similar to Wolfs et al., the length \( L \) in equation (1) was determined by the sum of the projected MLC leaf widths at the isocenter and the width \( W \) as the average aperture of the MLC leaves forming the field projected at the isocenter. Figure 2 illustrates the distribution of the EFS per treatment plan, for the gantry angles and treatment fields under study. The median EFS (red lines) for all treatment plans was smaller than 2 cm and no VMAT segments (outliers shown as red crosses) exceeded an EFS more than 3.5 cm. Due to the jaw tracking technique the collimator jaws are positioned as close as possible to the outer MLC leaf per control point. As all BM are treated simultaneously with a single isocenter technique, the field sizes shaped by the jaws are always larger than \( 3 \times 3 \, \text{cm}^2 \). Since the dose is mainly determined by these small field segments created by the MLC, a field size of \( 2 \times 2 \, \text{cm}^2 \) was chosen to perform the cross-calibration.

To take these dose rate variations on the detector response into account, the cross-calibration was performed at the nominal dose rate closest to the average dose rate of the treatment plan. Above findings lead to a new calibration procedure consisting of an individualized calibration per treatment plan. A difference in calibration factor up to \(-2.6\%\) and \(-2.5\%\) was seen for a \( 2 \times 2 \, \text{cm}^2 \) field relative to the by the manufacturer recommended \( 5 \times 5 \, \text{cm}^2 \) field for 6 MV and 6 MV FFF beams respectively. For the lowest used nominal dose rate closest of 800 MU/min, this had an influence of \(-1.8\%\) on the calibration factor relative to the maximum nominal dose rate of 1400 MU/min. Combining these effects, using a \( 2 \times 2 \, \text{cm}^2 \) and a dose rate of 800 MU/min relative to the manufacturer’s recommendations, can cause a difference up to \(-4.1\%\) for 6 MV FFF. The influence of the dose rate dependence is not relevant for 6 MV beams since the dose rate typically stayed constant at the maximum nominal dose rate.
of 600 MU/min in all 14 treatment plans (Figure 3). The relative difference in calibration factors in function of dose rate and field size are summarized in Table 2. The influence of the plan specific calibration on the dosimetric comparison obtained with the OCTAVIUS 1600SRS in the OCTAVIUS 4D phantom with SRS top for the fourteen treatment cases is illustrated in Figure 4. The dosimetric agreement between the measured and calculated dose is evaluated using a 3D $\gamma$ criterion of 2%/2 mm and a cut-off value of 80%. The agreement scores in red show the scores obtained using a default calibration and the scores in blue the scores obtained using a plan specific calibration. In the latter case, the mean agreement ± standard deviation (SD) improves from 92.3 ± 7% to 96.5 ± 4.6% and from 89.7 ± 11% to 96.6 ± 4% for 6 MV and 6 MV FFF beams respectively.

The comparison between absolute dose calculations and measurements obtained with the OCTAVIUS 1600SRS in the OCTAVIUS 4D phantom with SRS top for 14 treatment cases with 6 MV and 6 MV FFF beams is shown in Tables 3 and 4, respectively. We have found mean ± SD agreement scores of 98.6 ± 1.7%, 96.5 ± 4.6% and 97.3 ± 4.4% (6 MV) and 98.6 ± 1.5%, 96.6 ± 4.0% and 96.4 ± 6.3% (6 MV FFF) for the different cut-off values 50%, 80 and 95% respectively using 3D $\gamma$ criteria of 2%/2 mm. The relative deviations were defined as the difference between the maximum reference dose calculated by the TPS (TPS $D_{max}$) and the measured maximum dose (Measured $D_{max}$), referring to the maximum dose in the 3D measurement volume, divided by the maximum TPS dose. In general, the measurements yield lower results than the doses calculated by the Acuros XB dose calculation algorithm.

### DISCUSSION

For an accurate treatment of multiple BM with a single isocenter SRS VMAT technique, dedicated QA procedures and equipment are required. Besides an advanced planning technique, that requires at least a type B or C calculation algorithm and knowledge of small field dosimetry uncertainties, routine machine
Table 3. OCTAVIUS 4D measurement results (6 MV) with 3D γ criteria of 2%/2 mm (Agreement score), using cut-off values of 50%, 80%, and 95%

| Plan no. | Agreement score (%) cut-off | TPS $D_{\text{max}}$ (Gy) | Measured $D_{\text{max}}$ (Gy) | $\frac{(\text{TPS} \ D_{\text{max}} - \text{Measured} \ D_{\text{max}})}{\text{TPS} \ D_{\text{max}}}$ (%) |
|----------|-----------------------------|-----------------------------|-------------------------------|---------------------------------------------|
| 1        | 97.6                        | 95.6                        | 95.8                          | 11.1                                        |
| 2        | 98.8                        | 99.7                        | 98.2                          | 11.2                                        |
| 3        | 99.9                        | 99.9                        | 99.7                          | 10.3                                        |
| 4        | 99.6                        | 98.3                        | 100                           | 9.7                                         |
| 5        | 98.7                        | 95.1                        | 96.6                          | 9.7                                         |
| 6        | 98.6                        | 97.3                        | 83.3                          | 34.5                                        |
| 7        | 92.8                        | 80.7                        | 100                           | 29.7                                        |
| 8        | 99.6                        | 97.8                        | 100                           | 9.7                                         |
| 9        | 99.4                        | 98.3                        | 100                           | 11.0                                        |
| 10       | 99.6                        | 98.3                        | 100                           | 10.9                                        |
| 11       | 99.0                        | 98.3                        | 99.0                          | 10.6                                        |
| 12       | 99.5                        | 98.6                        | 96.2                          | 10.7                                        |
| 13       | 97.8                        | 95.8                        | 93.7                          | 10.6                                        |
| 14       | 98.1                        | 97.1                        | 100                           | 31.9                                        |

TPS, treatment planning system.

$D_{\text{max}}$ (Gy) is the maximum dose calculated by the TPS and measured.

Table 4. OCTAVIUS 4D measurement results (6 MV FFF) with 3D γ criteria of 2%/2 mm, using cut-off values of 50%, 80%, and 95% and $D_{\text{max}}$ (Gy) the maximum dose in the measurement volume of the OCTAVIUS 4D phantom calculated by the TPS and measured by the array detector

| Plan no. | Agreement score (%) cut-off | TPS $D_{\text{max}}$ (Gy) | Measured $D_{\text{max}}$ (Gy) | $\frac{(\text{TPS} \ D_{\text{max}} - \text{Measured} \ D_{\text{max}})}{\text{TPS} \ D_{\text{max}}}$ (%) |
|----------|-----------------------------|-----------------------------|-------------------------------|---------------------------------------------|
| 1        | 98.2                        | 96.0                        | 100                           | 10.7                                        |
| 2        | 99.6                        | 99.0                        | 100                           | 10.5                                        |
| 3        | 99.9                        | 99.8                        | 100                           | 10.4                                        |
| 4        | 99.9                        | 99.5                        | 96.3                          | 9.8                                         |
| 5        | 98.5                        | 94.5                        | 95.8                          | 9.9                                         |
| 6        | 97.0                        | 97.5                        | 85.7                          | 35.0                                        |
| 7        | 95.2                        | 92.7                        | 100                           | 33.2                                        |
| 8        | 99.6                        | 98.4                        | 100                           | 9.7                                         |
| 9        | 99.4                        | 99.9                        | 100                           | 11.0                                        |
| 10       | 99.8                        | 98.1                        | 100                           | 10.9                                        |
| 11       | 98.7                        | 96.6                        | 100                           | 10.7                                        |
| 12       | 98.7                        | 98.3                        | 93.5                          | 10.4                                        |
| 13       | 95.8                        | 83.9                        | 78.6                          | 10.8                                        |
| 14       | 99.5                        | 98.4                        | 100                           | 32.3                                        |

FFF, flattening filter free; TPS, treatment planning system.
QA assures the correct execution of the mechanical requirements of the treatment technique. Accurate 3D dosimetric verification is the last hurdle for an accurate and safe implementation of the treatment technique.

Since the BM can have very small volumes, down to 0.08 cm$^3$ according to the treatment plans in this work, a detector with a high spatial resolution is required. Radiochromic films offer high spatial resolution and excellent response characteristics but the experimental evaluation is limited to 2D planes which in most cases covers only part of the BM present in a treatment plan. Another disadvantage of the film procedure is that it is very labor intensive and the results are available the next day at the earliest. The OCTAVIUS 1600SRS array detector, which is the successor of the 1000SRS array detector, has an inner spatial resolution of 2.5 mm with an extended measurement range of $15 \times 15$ cm$^2$. Using the 1000SRS detector, only 65% of all BM in our clinical treatment plans under study fit inside the measurement field-of-view (FOV). Due to the expanded measurement range, all except one lesion fit inside the measurement FOV of the 1600SRS detector while maintaining the excellent resolution. The 1600SRS array combined with the OCTAVIUS 4D phantom makes it possible to measure multiple widely spaced target volumes treated with coplanar and non-coplanar beams in a single measurement with immediate results. An accurate cross-calibration is required using set-up conditions that are representative of the VMAT segments in the clinical treatment plans. The field-size dependence of the detector response is taken into account by determining the EFS of the VMAT segments in the treatment plans. For all treatment plans described in this manuscript the median EFS were smaller than 2 cm. A calibration field size of $2 \times 2$ cm$^2$ was considered to be small enough to represent the EFS of the VMAT segments in the treatment plans and large enough to avoid errors in calibration due to set-up uncertainty. Similarly, the average dose-rate is used to account for losses due to recombination by performing a cross-calibration at the nominal dose rate closest to the average dose rate of the treatment plan. When these influences are not taken into account this can lead to combined dose differences up to 4.1% for 6 MV FFF beams for our treatment plans. These differences can lead to a systematic shift of the measured dose. Cross-calibrating with a pinpoint IC has the advantage that the system requires no data input from the linac nor the TPS for the measurement and leads to a completely independent dose verification. A plan specific calibration with the pinpoint IC can also be applied to measurements using the 1000SRS detector because it features similar technology than the 1600SRS detector. For the 14 treatment cases described in this manuscript, the comparison between absolute dose calculations and the measurements yield high agreement scores for both 6 MV and 6 MV FFF energies. This indicates that the described measurement method can be used for a variety of treatment cases ranging in treatment technique, fractionation scheme, amount of BM and spatial arrangement of the BM.

**CONCLUSION**

The rotational OCTAVIUS 4D phantom in combination with a recently developed high resolution 1600SRS array detector offers an accurate solution to perform routine QA measurements for treatments with multiple BM, which is gaining more attention over the last years. Unlike the recommendation by the manufacturer, we advise that the cross-calibration is performed:

- with a field size corresponding to the average equivalent square field size of the treatment plans;
- with a dose rate corresponding to the average dose rate of the treatment plan per treatment plan.

Otherwise, a systematic dose deviation (in our case up to 4.1%) could occur in the dosimetric verification of single isocenter SRS treatment plans of brain metastases.

**ACKNOWLEDGMENTS**

The authors would like to thank PTW-Freiburg for providing the OCTAVIUS 1600SRS detector array and for the valuable discussions on the array specifications. Further, we thank Cecile Wolfs and Renate van Doormaal for her help in the specification of equivalent field sizes per clinical treatment plan.

**REFERENCES**

1. Kraft J, Zindler J, Minniti G, Guckenberger M, Andratschke N. Stereotactic radiosurgery for multiple brain metastases. Curr Treat Options Neurol 2019; 21: 6. doi: https://doi.org/10.1007/s11940-019-0548-3
2. Kirkpatrick JP, Wang Z, Sampson JH, McSherry F, Herndon JE, Allen KJ, et al. Defining the optimal planning target volume in image-guided stereotactic radiosurgery of brain metastases: results of a randomized trial. Int J Radiat Oncol Biol Phys 2015; 91: 100-8. doi: https://doi.org/10.1016/j.ijrobp.2014.09.004
3. Hanna SA, Mancini A, Dal Col AH, Asso RN, Neves-Junior WFP. Frameless image-guided radiosurgery for multiple brain metastasis using VMAT: a review and an institutional experience. Front Oncol 2019; 9(August): 1-11. doi: https://doi.org/10.3389/fonc.2019.00703
4. Clark GM, Popple RA, Young PE, Fiveash JB. Feasibility of single-isocenter volumetric modulated Arc radiosurgery for treatment of multiple brain metastases. Int J Radiat Oncol Biol Phys 2010; 76: 296–302. doi: https://doi.org/10.1016/j.ijrobp.2009.05.029
5. Vergalasova I, Liu H, Alonso-Basanta M, Dong L, Li J, Nie K, et al. Multi-Institutional dosimetric evaluation of modern day stereotactic radiosurgery (SRS) treatment options for multiple brain metastases. Front Oncol 2019; 9(JUN): 1–12. doi: https://doi.org/10.3389/fonc.2019.00483
6. Roper J, Chanyavanch V, Betzel G, Switchenko J, Dhabaan A. Single-Isocenter Multiple-Target stereotactic radiosurgery: risk of compromised coverage. Int J Radiat Oncol Biol Phys 2015; 93: 540–6. doi: https://doi.org/10.1016/j.ijrobp.2015.07.2262
7. Tryggestad E, Christian M, Ford E, Kut C, Le Y, Sanguineti G, et al. Inter- and intrafraction patient positioning uncertainties for intracranial radiotherapy: a study of four frameless, thermoplastic mask-based immobilization strategies using daily cone-beam CT. Int J Radiat Oncol Biol Phys 2011;
80. Br J Radiol;94:20210473
81. Jeevanandam P, Agnew CE, Irvine DM, et al. Consideration of optimal isodose surface selection for target coverage in micro-multileaf collimator-based stereotactic radiotherapy for large cystic brain metastases: comparison of 90%, 80% and 70% isodose surface-based planning. Br J Radiol 2012; 85: e640–6. doi: https://doi.org/10.1259/bjr/21015703
82. Clark GM, Poppel RA, Prendergast BM, Spencer SA, Thomas EM, Stewart JG, et al. Plan quality and treatment planning technique for single isocenter cranial radiosurgery with volumetric modulated arc therapy. Pract Radiat Oncol 2012; 2: 306–13. doi: https://doi.org/10.1016/j.prro.2011.12.003
83. Ohira S, Ueda Y, Akino Y, Hashimoto M, Masaoka A, Hirata T, et al. HyperArc VMAT planning for single and multiple brain metastases stereotactic radiosurgery: a new treatment planning approach. Radiat Oncol 2018; 13: 1–9. doi: https://doi.org/10.1186/s13014-017-0948-z
84. Knöös T, Wieslander E, Cozzi L, Brink C, Fogliata A, Albers D, et al. Comparison of dose calculation algorithms for treatment planning in external photon beam therapy for clinical situations. Phys Med Biol 2006; 51: 5785–807. doi: https://doi.org/10.1088/0031-9155/51/22/005
85. Fogliata A, Nicolini G, Clivio A, Vanetti E, Mancosu P, Cozzi L. Dosimetric validation of the Acuros xB advanced dose calculation algorithm: fundamental characterization in water. Phys Med Biol 2011; 56: 2885–6. doi: https://doi.org/10.1088/0031-9155/56/9/2885
86. Makris DN, Pappas EP, Zoros E, Papankouloa N, Saenz DL, Kalaitzakis G, et al. Characterization of a novel 3D printed patient specific phantom for quality assurance in cranial stereotactic radiosurgery applications. Phys Med Biol 2019; 64: 105009. doi: https://doi.org/10.1088/1361-6560/ab1758