

# Evaluation of HyperArc™ using film and portal dosimetry quality assurance

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## Research Article

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# Abstract

HyperArc™ is a stereotactic radiotherapy modality designed for targeting multiple brain metastases using a single isocenter with multiple non-coplanar arcs. The purpose of this study was to assess the efficacy of two patient specific quality assurance methods, film and the Varian Portal Dosimetry System with Varian's HyperArc™ technique and raise important considerations in the customisation of patient specific quality assurance to accommodate HyperArc™ delivery. Assessment criteria included gamma analysis and mean dose at full width half maximum. The minimum met size, maximum off-axis distance and suitable energy were identified and validated. Patient specific quality assurance procedures were applied to a range of clinically relevant brain met plans. Initial investigation into energy selection showed no significant differences in gamma pass rates using 6MV, 6MV FFF or 10MV FFF for met sizes greater than 15 mm diameter at the isocenter. Gamma pass rates (2%/2mm) for 15 mm mets at the isocenter for all energies were greater than 96.0% for portal dosimetry and greater than 98.7% for film. Fields of size 15 mm placed at various distances (10–70 mm) from the isocenter resulted in a maximum mean dose difference of 1.5% between film and planned. Clinically relevant plans resulted in maximum mean dose difference for selected mets of 1.0% between film and plan and maximum point dose difference of 2.9% between portal dose and plan. Portal dose image prediction was found to be a quick and convenient quality assurance tool for mets larger than 15 mm near the isocenter but provided diminished geometrical relevance for off-axis mets. Film QA required exacting procedures but offered the ability to assess the accuracy of geometrical targeting for off-axis mets and provided dosimetric accuracy for mets to well below 15 mm diameter.

## Introduction

HyperArc™ has provided a single isocentric technique for delivering radiation to multiple brain mets (BM). One of the driving forces behind this emerging technology is the increase in patients presenting with BM. Demographic studies have shown [1] that up to 8.5% of patients developed BM within five years of primary diagnosis with the number of patients presenting with BM increasing due to extension of life based on curative primary treatment. Treatments for brain metastases [2] currently range from surgery, chemotherapy, use of steroids, and radiation therapy [3][4]. Whole brain radiation therapy was one of the earliest applications of radiation treatment for multiple intracranial tumours and prophylaxis for microscopic disease. In this type of delivery there are limited to various degrees of sparing radiosensitive intracerebral structures like the optic chiasma, cochlea and hippocampus [5]. Other current radiosurgery modalities for BM are dominated by the adopted gold standard Gamma Knife but are not widely available to the general public with only limited number of Gamma Knife machines in Australia [6]. External beam radiation with linacs is becoming more commonly available with an increasing proportion commissioned for stereotactic radiation therapy (SRT) techniques for single to oligometastatic brain mets [7]. The number of mets able to be successfully treated with a single isocenter technique are limited by the complexity of the treatment planning system (TPS) and the machine's ability to deliver the intended technique.

HyperArc™ offers a potential solution to the complexities facing multiple BM treatments [4]. It is a stereo technique available with TrueBeam™ version 2.7 or higher, offering an optimised single isocenter, MLC based,

non-coplanar multiple PTV planning solution. It also offers a clinically lean delivery time for patient comfort and able to conform radiation to multiple BM (up to 13 mets in this project) while sparing organs at risk. This stereotactic radiation technique is an optimised and automated form of volumetric modulated arc therapy with Eclipse' ability to plan MLC conformality to multiple targets over at least one couch kick. The patient is immobilised in a dedicated frameless fixation device by QFix's Encompass™ (Fig. 1) support [8] which is attached to a PerfectPitch™ six degrees of freedom couch (6DOF) [9]. The thermoplastic material (Fig. 1) provides cranial immobilisation along with radiopaque markers used by the TPS during the planning process.

Comprehensive quality assurance (QA) for SRT requires a comprehensive procedure to minimise errors and uncertainty [10] due to the nature of the hypofractionated deliveries to small target volumes with rapid dose fall-off [11]. Intracerebral lesions vary in size with many presenting with diameters less than 10 mm. The small targets raise small field dosimetry challenges. Chamber ionisation measurements is the gold standard for point dose measurements but unsuitable for many of these small sized mets due to compromised volume averaging of chamber, lateral charged particle disequilibrium and potential source occlusion [12].

Film offers good dose accuracy and superior resolution, near water equivalence, excellent uniformity, minimal energy dependence and its use is easily integrated by most phantoms [13]. Film is considered the gold standard for high resolution dosimetry [13] but avoided for patient specific QA in favour of quicker and more convenient alternatives. The inclusion of Varian's portal dose image prediction (PDIP) with patient specific QA has already been widely used for techniques such as intensity modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) for single mets [14].

Portal dosimetry has emerged as an extension of the electronic portal image device (EPID) initial intent of imaging. In essence, the image data collected by the EPID is calibrated relative to a unit (CU) to provide dose equivalence [15]. The collected data is compared to predicted data attained through a modelled algorithm. The EPID solution for dosimetric checks is popular due its already standard availability for imaging, minimal set-up, its immediate 2D high-resolution images and seamless software integration to provide quick analysis. Varian's PDIP solution is already widely used for VMAT patient specific QA for single lesion sites [14]. The 2D reconstruction model [16] is based on data received from the EPID which is non-inclusive of couch/couch kicks and phantom involvement.

This paper assesses the efficacy of these patient specific QA methods for HyperArc™ and highlights important considerations in customisation.

## Methods

Portal Dosimetry (Varian Medical Systems, Palo Alto, USA) was the integrated patient specific QA system used in this project. It was used to acquire images of the measured fluence delivered from a Varian TrueBeam Platform version 2.7 while the Eclipse™ (v. 15.6.03, Varian Inc.) planning system was used to generate a modelled dosimetric predicted image. The verification plan was delivered directly to the EPID with the detector at an optimal distance of 100 cm from source. Dosimetric adaptation of the portal imager

involved calibrating the acquired fluence to a CU to provide a form of absolute dose equivalence. The calibrated data was then compared to the predicted data attained through a modelled algorithm. The portal dose prediction calculation used the Portal Dose Image Prediction (PDIP) algorithm. Various QA tools for gamma analysis and point/profile dose were available with Aria RTM 16.1 Portal Dosimetry to determine plan validity [16]. Portal dosimetry was used on a Varian TrueBeam™ linear accelerator with an aS1200-II EPID panel. Suitability of the panel for the HyperArc™ technique with flattening filter free (FFF) energy, lesion size and high number of monitor units was initially checked by its specifications[16] [17]. The detector panel had an active area of 40.0 x 40.0 cm<sup>2</sup> with a pixel matrix of 1024 x 1024 pixels attaining a resolution of 0.0393 cm. Saturation occurred at dose rates above the maximum energy used and beam fluence was captured at SSD 100 cm. The fluence map collected, normalised to the center pixels of the panel, were calibrated to 1 CU to correspond to 100 MU at 100 cm SSD with 10 x 10 cm<sup>2</sup> field for each energy [18]. Constancy checks for output and uniformity were performed on a daily basis for each energy as per AAPM TG-142 [19] report recommendation. Varian's Machine Performance Check (MPC) [20] was used for these daily checks and verified beam constancy for PDIP verification plans.

The patient specific QA procedure for portal dosimetry required a verification plan to be created from the patient plan. Test cases were planned with Acuros (v 15.6.03) from which portal dose imaging prediction PDIP (v 15.6.03) verification plans were generated. The EPID had been commissioned for PDIP with checks covering variable dose rates, linearity, ghosting, output factors and intensity profile accuracy.

Film QA used both GafChromic EBT3 and EBT-XD with the latter used where the prescription dose exceeded 10 Gy [21]. Films were exposed using LAP's Easy Cube [22] where the modular inserts made it a useful tool for stereotactic dosimetry. The CIRS 30 cm x 30 cm slabs were initially trialled since they are commonly available in most physics departments and water equivalent however, due to their size excluded the use of the Encompass™ couch. The Easy Cube's smaller size enabled it to be placed in the Encompass™ couch and its 18 cm sided cubic volume large enough to encompass the geometric range of intracranial mets. The Easy Cube's polystyrene RW3 composition was not water equivalent, however the composition was taken into account by the Acuros TPS algorithm[18]. The built-in radiopaque markers allowed for image guidance localisation. Films were scanned with an EPSON 1100 XL flatbed scanner following well documented QA procedures [23], [24], [25], [26], [27]. A calibration file for each batch of EBT-XD and EBT3 GafChromic film was acquired using CIRS solid water slabs. The pixel value function [26] was dosimetrically validated with independent reference fields and rescaled during the patient QA checks with plan specific reference fields [26], [28].

The HyperArc™ patient verification plans were calculated with dose to water ( $D_w$ ) by the Acuros algorithm with grid resolution and CT slice thickness both at 1 mm.  $D_w$  in transport medium was used with Acuros [16] since the film calibration was based on dose to water calculations. Coronal plane profiles were exported with a pixel resolution of 0.195 px/mm. Delivery of HyperArc™ patient plans in this project consisted of four arcs with 3 couch-kicks  $\pm 45^\circ$  and  $90^\circ$  from the sagittal plane. The kV/MV isocenter coincidence was checked through the Winston-Lutz (WL) test [29] before HyperArc™ delivery. AAPM TG 142 [19] was referenced for the tolerances on the mechanical checks. Film was placed parallel to the coronal plane in the Easy Cube,

marked with fiducials for laser alignment and then localised with a CBCT on a 6DOF couch. Any shift applied to the phantom was noted as this would affect the film/TPS registration in analysis. Every treatment plan delivery was accompanied by a calibration film as per protocol outlined by Lewis et al [24] to account for variation in machine daily output and film scanning conditions.

The scanned 48 bit 0.358 px/mm film images were analysed using Ashland's FilmQAPro 2015 software. Each BM was initially analysed by comparing the FWHM and mean dose to validate dosimetric equivalence for the mets at various off-axis (OA) distances. Gamma analysis was then acquired for each met with gamma pass rate criteria set at dose difference of 2%, distance to agreement (DTA) set to 2 mm with a 10% threshold. Selection of the region of interest (ROI) was localised to the surrounding area of the BM.

The methods outlined in this section cover validation of film and PDIP dosimetry for multi-mets, geometrical and dosimetric uncertainties in the QA process for single and multi-met HyperArc™ analysis and BM case studies.

Although film and PDIP patient specific QA procedures were already established in the department, validation of a higher dose range for SRS mets and scanning of multi-mets was required. SRS plans generated maximum dose in excess of fractionated SRT plans and required extended dosimetric validation of calibration files for both EBT-XD and EBT3. Known issues as addressed by Chen et al [30] regarding variable scanning response in the lateral direction was potentially an issue for scanning multiple mets on a single film. Checks were done by scanning a range of exposed film for both EBT3 and XD over a range of 50 mm from the central longitudinal axis of the EPSON 1100 XL flatbed scanner. The ROI measuring the pixel values (PV) for each film strip were measured for both red and green channels. Percentage differences between the averaged 50 mm lateral off-set PV were compared to the central axis PV. Based on these results, recommendations were made for scanning films with multiple off-axis mets and the selection of appropriate colour channel for all other measurements pertaining to the remainder of this project.

A range of tolerances and criteria were investigated by Miften et al., [33] for SRT/ SRS techniques from which dosimetric and geometric tolerances were nominally set 2%/2mm. These were selected to test patient QA processes, provide baselines for future development and were within the scope of machine deliverability. Film QA processes required investigating to determine the sources of greatest uncertainty due to inclusion of extended SRS dose range and multi-met film exposures. A film calibration curve model will vary from data measured due to the nature of curve fitting [27] and may vary at key points by greater than 2%. Variances in machine output, scanner temperature and film development time all caused further dosimetric uncertainty however, these uncertainties were minimised by the inclusion of reference films [23]. Checks were performed to determine maximum variation of a range of exposed films of known dose over the range of the film calibration. Checks were performed to determine the geometric shifts required in the film QA gamma optimisation process for multi-mets. WL checks were recorded over period of 8 months with the requirement that tests would be repeated if a maximum delta shift was above 1 mm.

Single met plans were created using the HyperArc™ planning technique for mets 10–25 mm diameter at the isocenter with energies 6MV, 6FFF, and 10FFF. Each plan was prescribed to a single dose of 10 Gy with each

plan using four non-coplanar arcs. Gamma values were acquired from both PDIP and Film QA Pro 2015. FWHM comparisons were measured for film and compared with the TPS. The FWHM was not a relevant measure with PDIP due to its 2D integral fluence. Based on the outcome of these results, target volume (TV) size limits would be recommended for both PDIP and film for the remainder of this project.

Multi-met plans were created with HyperArc™ for 20 mm TVs spaced at diagonal distances of 10 mm, 20 mm, 50 mm and 70 mm (see Fig. 2) from the isocentre. The TVs were placed diagonally so that OA distances in both in-plane and cross-plane axes were investigated. Each TV in each single fraction plan had a prescription dose of 10 Gy. The diagonal OA met plans were delivered using 6MV, 6MV FFF, and 10 MV FFF energies. Checks were performed to determine if there was any dosimetric dependency on distance of the TV from the isocenter. PDIP and film gamma analysis were acquired based on ROI relative to the TV with 2%/2mm criteria. FWHM and mean dose was measured for each TV for film and compared to the TPS plan. The FWHM was averaged over the in-plane and cross-plane measurements.

Based on these results, met OAD limits and beam energy would be recommended for both PDIP and film.

Case studies were sampled from a set of previously treated BM patients from a sister site which used BrainLAB for their TPS. The plans were anonymised and re-planned using HyperArc™. From the range of eleven case studies, four were selected to represent a range of possible multi-met scenarios. Having determined patient specific QA guidelines on size limits for TVs, off-axis geometry, each of the four representative plans were initially screened against these guidelines. For each plan, this included an analysis of the size and location of each lesion, its proximity to organs at risk such as brain stem, optic chiasm and proximity to bone and to other lesions and lesion morphology. Mets not able to be delineated by the width of a single 5 mm pair of MLC leaves were planned as a single TV. Film QA was measured in the coronal plane of the TV's near maximum dose. All of the selected test cases presented with at least seven lesions, making the chance of any one coronal plane intersecting more than one lesion high. In these cases, flexibility in coronal plane positioning was optimised to near maximum dose in multiple lesions. The phantom was setup in the Encompass™ couch and registered using CBCT. Due to limited number of slab combinations, some plans were required to be delivered more than once to have films placed in the correct coronal plane.

## Results

The percentage difference between pixel value variation for a range of exposed films placed 50 mm laterally from the center of the scanner resulted in the green channel varying by less than 0.7% for either XD and EBT3 film while the red channel varied by less than 3.6% (see Fig. 3). The PV variation did not increase for the green channel based on increase in exposure for either XD or EBT3 films. Although EBT3 can be used beyond the vendor's recommended optimal dosimetric range of 10 Gy, XD was used for the remainder of the project.

Recommendations for project scope limited scanning to within 50 mm of central longitudinal axis of scanner bed using the green channel. If distances between BM ranged beyond 100 mm in the scanning plane, then it was recommended that each BM should be scanned separately along central longitudinal axis.

The max dosimetric variation with the green channel for EBT3 film was 0.8% and for XD, 0.7%. The inclusion of the reference film accounts for daily output and scanning deviations enabling the film QA workflow to less than 2% uncertainty.

Geometric shifts were monitored over the range of multi-mets delivered in the in-plane and cross-plane directions during the film QA gamma optimisation for multi-mets. Shifts of  $0.8 \pm 0.4$  mm in the in-plane and  $0.9 \pm 0.6$  mm in the cross-plane were noted for optimising gamma results.

Single met analysis was based on 95% gamma pass rate using 2%/2 mm criteria. All energies showed dosimetric agreement for lesions down to a size of 15 mm diameter. The lowest gamma value for film was 98.7% corresponding 10 MV FFF beam with a 10 mm TV. PDIP results started to deteriorate with TVs less than 15 mm.

Table 1  
*Gamma Analyses for Single Mets* provided an avenue to use film for smaller mets.

<b>Gamma Analysis Criteria 2%/2mm 10% [Tolerance = 95%]</b>				<b>FWHM</b>
<b>CAX TV Size</b>	<b>Energy</b>	<b>Film %</b>	<b>PDIP %</b>	<b>Film-TPS (mm)</b>
25 mm	10 MV FFF	100.0%	99.8%	-0.7
	6 MV FFF	100.0%	100.0%	-0.8
	6 MV	98.7%	100.0%	-0.6
20 mm	10 MV FFF	100.0%	100.0%	-0.7
	6 MV FFF	99.7%	99.5%	-0.9
	6 MV	100.0%	95.9%	-0.5
15 mm	10 MV FFF	98.8%	98.7%	-0.9
	6 MV FFF	100.0%	96.0%	-0.8
	6 MV	99.8%	97.6%	-1.2
10 mm	10 MV FFF	98.8%	63.0%	-0.6
	6 MV FFF	99.0%	86.7%	-1.4
	6 MV	100.0%	90.2%	-1.1

Each lesion was analysed by its local ROI which could be varied to provide a better  $\gamma$  result. Tolerance cut-off of 10% limited the impact of the varied ROI.

The FWHM differences between TPS and film were averaged for measurements in the in-plane and cross-plane directions and resulted in less than 1 mm agreement for 10MV FFF for all TVs. The TPS model consistently overestimated the FWHM in both planes and could be an indicator that the TPS model may require verification and refinement for small fields. Due to limitation of PDIP results, TV were restricted to diameters greater than 15 mm for the multi-met analyses.

Multi-met gamma results for all energies with film were greater than 97% however, PDIP produced mixed results with the flattened 6x beam greater than 91.6%. The gamma results for the unflattened beams deteriorated with increasing OAD. Results for the difference in FWHM for film and TPS (Fig. 4) indicated TV coverage was slightly less for film than planned for unflattened beams and that this difference increased more noticeably for larger OA distances.

The mean dose difference between film and TPS (Fig. 5) indicated no dependency on OAD for all three energies tested.

Based on results from multi-met analyses, 10 FFF was selected for use in the case studies. The maximum change in FWHM (Fig. 4) was less than 1.0 mm with gamma analyses greater than 98.8% for TVs down to 10 mm.

Case study results are listed in Table 2 for BM of average diameters ranging from 7–26 mm. Each case study contained BMs below the diameter guideline of 15 mm and test case 2 only had mets below the suggested guideline from the single met results. PDIP peak CU differences were averaged over a range of peaks from each plan with only one plan registering a CU difference less than 2%. Gamma analysis for each PDIP plan was calculated based on the whole plane since localising ROI of individual mets was problematic due to fluence smearing with all results out of tolerance. Gamma analysis for film were all greater than 98.4% for each TV and the difference in FWHM was less than 1 mm. The average mean dose difference between TPS and film was 1.0%

Table 2  
Patient specific film and PDIP QA results for case studies 1–4 using  $\gamma$  analyses and FWHM

Test Case	Brain Met	Brain Met Dimensions (mm)	Avg PDIP CU diff (%)	PDIP $\gamma$ 2%,2mm (%)	Film $\gamma$ 2%,2mm (%)	FWHM TPS-Film (mm)
<b>1</b>	All mets (PDIP)		-1.4	<b>71.5</b>		
	BM 1	13*13			99.7	0.9
	BM 2	18*16			99.7	0.6
	BM 3	10*17			98.8	0.9
	BM 4	20*14			98.8	0.1
<b>2</b>	All mets (PDIP)		-5.3	<b>83.1</b>		
	BM 1	9*8			99.9	0.3
	BM 2	8*8			98.9	1.0
<b>3</b>	All mets (PDIP)		-3.9	<b>75.8</b>		
	BM 1	16*17			99.4	0.5
	BM 2	17*14			99.1	0.4
	BM 3	20*24			99.1	-0.7
<b>4</b>	All mets (PDIP)		-2.8	<b>77.4</b>		
	BM 1	26*22			98.4	0.5
	BM 2	7*7			100.0	-1.0
	BM 3	22*12			98.4	0.3

## Discussion

Variable lateral scanner response is a well-documented effect [30] and needed to be investigated due to the possibility of scanning multiple BM in the one coronal plane and as a matter of instilling confidence in established film analyses procedures. The higher sensitivity of the red channel [31] made it more prone to lateral scanning factors especially in the higher dose regions. The differences in the response with GafChromic's EBT3 and XD can be attributed to EBT3's greater sensitivity and corresponding effect of amplifying the lateral artefact response as noted by Lewis et al [32]. The lateral variation response across the red and green channels were considered with multi-met scans however, lateral factors were largely ruled

out by scanning films along the same longitudinal axis where the calibration films set were scanned. In addition, ROI pertaining to each BM could be analysed individually thereby enabling each BM to be scanned along the central longitudinal axis of the scanner. The processes for film QA are well documented by Lewis et al [24] and these should be systematically adhered to so as to lessen the dosimetric measurement uncertainty.

Point dose and mean dose measurements were able to be analysed by film and to a lesser meaningful extent by PDIP as a measure of peak CU due to the smearing of the fluence. Comparison of peak dose with measured and predicted for PDIP also proved ambiguous due to varying outcomes based on point selection. Determination of point dose and mean dose comparisons were important to confirm minimum dose coverage to a met and could be used to determine maximum dose to adjacent organs at risk like the brain stem. The film QA process could determine systematic over and under dose estimation at specific regions by the planning system however this ability was lost in PDIP due to the 2D fluence integration process. Max dose with HyperArc™ may depend on how the prescription is applied with steeper dose gradients and higher dose maximums attained by prescribing to a lower isodose [3]. Steeper gradients to the PTVs allowed for less dose wash to nearby OAR. The FWHM metric as outlined by Milften et al [33], provided quantitative analysis of coverage which is an important metric for high grade tumour control, is measurable in film but not with PDIP. Along with FWHM, PDIP's lack of geometric relevance was a concern when the BM being analysed was near an OAR. Bresciani et al [34], notes that PDIP's 2D reconstruction algorithm lacked anatomical or geometrical relevance however, this could be addressed by a 3D forward projection technique. The nature of max dose points may also not be a leading concern where lesion ablation is one of the goals in stereotactic treatment in which case dosimetric tolerances may opt for a greater margin than 2% as canvassed by Milften et al [33]. Likewise, DTA could have been reduced to 1 mm to provide greater sensitivity for QA outcomes for mets with varying OAD, morphology or neighbouring OAR.

Gamma analysis covered both the essential dosimetric and geometric properties for clinical delivery of SRS/SRT techniques [33]. SRS and SRT require tight margins for PTV and consequently rely on dedicated patient immobilization offered by systems such as the Encompass™, superior patient positioning such as 6DOF, SRT compliant Linac tolerances such as kV/MV coincidence and a tight radiation isocenter sphere. WL. Halvorsen et al., [11] states the main criteria for implementation of SRS besides hypofractionation is the approximate 1 mm accuracy margin requirement for intracranial targets. Crow, S et al follows in his technical note [35], that the application of  $\gamma$  metrics for dosimetry and DTA should be applied in such a way as to prioritize the property of greatest clinical importance. Steep dose gradients for example can easily fail the dosimetric quality of the  $\gamma$  test where a 1 mm shift can amount to 20% dose difference however, a 2 mm DTA could still provide a  $\gamma$  pass for this point. The results may provide over estimated  $\gamma$  results which may overlook coverage to the target volume.

The multi-met analyses included investigating the FWHM (Fig. 4) and mean dose (Fig. 5) for each TV in the TPS HyperArc™ plan. It was important to investigate properties of mean dose and FWHM consistency across OA distances since any variation could point to potential issues with the unflattened beam model or mechanical tolerance with couch rotation or kV/MV tolerances. These properties lost their dosimetric relevance when measured with PDIP. The portal image in Fig. 6 for a three met plan single arc highlighted

the spread of fluence captured by the 2D integrated process. A peak CU comparison for the TV placed at the isocenter was feasible in this case since high dose regions were visible in the red region and could provide useful comparisons of percentage over/under dose however, the peak CU characteristic was further compromised when the TVs were further off-axis with no visible concentration of peak CU. In contrast, film fluence map (Fig 2) provided the ability to determine mean dose and determine coverage with FWHM. The SRS techniques are ablative by design and may not consider the maximum dose in the TV as important as minimum coverage. The FWHM comparisons did indicate (Fig. 4) that TPS coverage was greater when measured with unflattened beams for off-axis TVs. This is a feature that would require further investigation and may not be detectable in gamma analysis results where DTA is 2 mm.

The selection of 10FFF for the case studies was in part due to the verification of single and multi-mets analyses but also due to the lower beam on time. The 10FFF high dose rate of 2400MU/min reduced risk of intrafraction movement and the filter free beams reduced scatter to the patient as also noted by Miften et al., [33]. The FFF beams non-uniformity potentially counteracted the benefit of lower beam on time especially for those mets with larger OAD however, film QA was able to confirm acceptable dose distributions for OA mets and the use of unflattened beams were supported in studies by Smith et al., [36]. An added complication to the FFF dose non-uniformity resulted in the varying modulation required by the TPS to deliver the same prescription to a range of mets at varying off-axis distances. In order to account for the non-uniformity for OAD mets, central mets required more modulation in order to collimate excess dose and was a consideration when selecting mets to analyse. This also prompted the isocenter to be optimally placed such that off-axis distances to mets were overall minimal. From the cases that were analysed, no noticeable differences were identified in the individual BMs analysed.

The PDIP QA process was a far less time-consuming process compared to film QA and gave immediate results. The software tools allowed for individual and composited field analysis and ROI could be localised around a target met. The lack of geometric relevance (Fig. 7a) for multi OAD mets made localising a ROI an unproductive task. The PDIP QA process also excluded beam attenuation and scatter through phantom and the mechanical variation generated by the HyperArc™ plan's three couch kicks. Based on the single and multi-met results, the cases studies (see Table 2), resulted in largely out of tolerance gamma analyses and peak dose comparisons due to the large number of small mets. The individual arcs for PDIP were also analysed with 2 out of 16 arcs resulting in a peak CU difference less than 2%. The multi-met study alluded to potential issues with the prediction model for small fields or with FFF intensity fluence maps which required further investigation outside the scope of this project. Out of the original eleven case studies, four cases were selected however, none of these cases would have been treated if the minimum PTV size of 15 mm was the deciding metric. All cases had small lesions with case study 3 having a 7 mm diameter.

The film mean dose percentage differences (Table 2) varied by a surprising minimal amount and likely to be a product of very controlled film procedures and of localised film scans of mets rather than as a single scan as was applied to the multi-met analysis which produced more realistic results (Fig. 5).

## Conclusion

PDIP potentially provided a quick tool for HyperArc™ patient QA checks for SRS/SRT however, due to a lack of geometric relevance for off-axis mets, restriction in lesion size, and the non-inclusion of geometric uncertainty of three couch-kicks PDIP does not provide a sufficient basis for meaningful patient QA. PDIP would require development with optimising the prediction algorithm and/or detector fluence factors along with supplementary machine QA to ensure integrity of kV/MV isocenter tolerance. Film QA provided high resolution geometric relevance and meaningful  $\gamma$  analysis for small lesions when a strict methodology was followed and suitable for use for HyperArc™ patient QA.

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## **Competing Interests**

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## **Authors Contributions**

*All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Onno Kamst, and Pushkar Desai. The first draft of the manuscript was written by Onno Kamst and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.*

## **Ethics approval**

*This research was conducted without the need for human or animal involvement and consequently did not require ethics approval.*

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## Figures

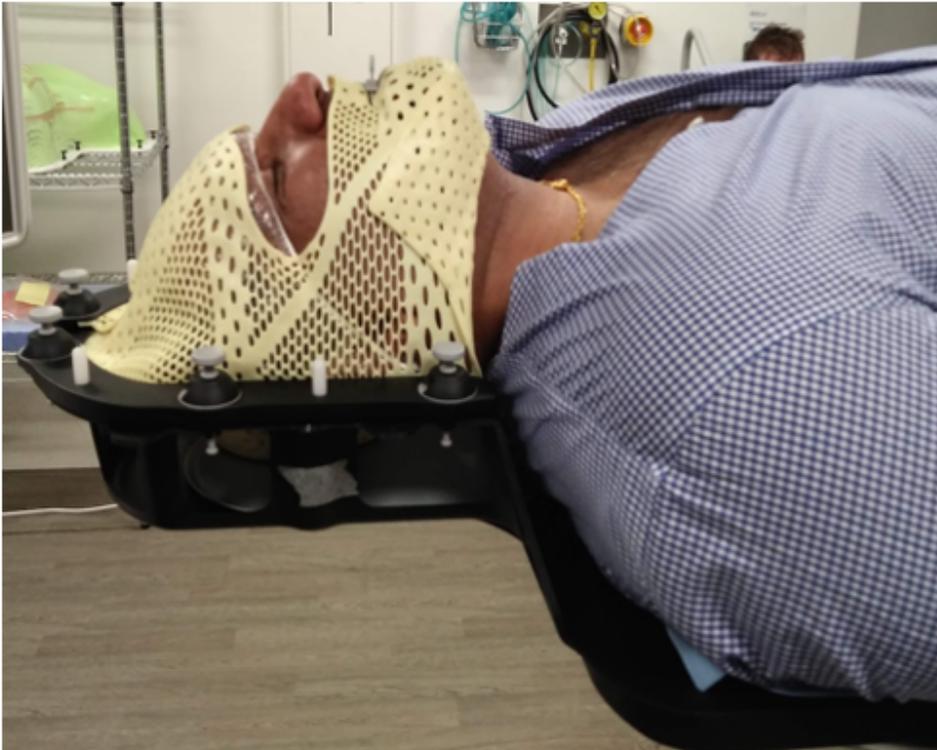
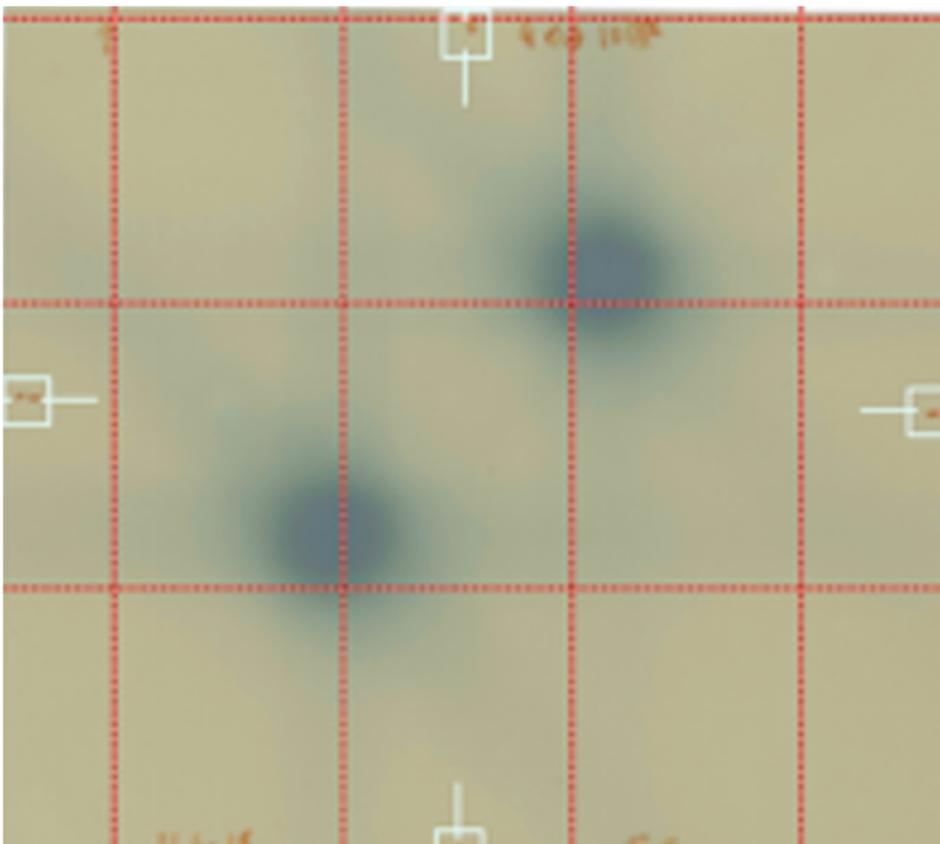


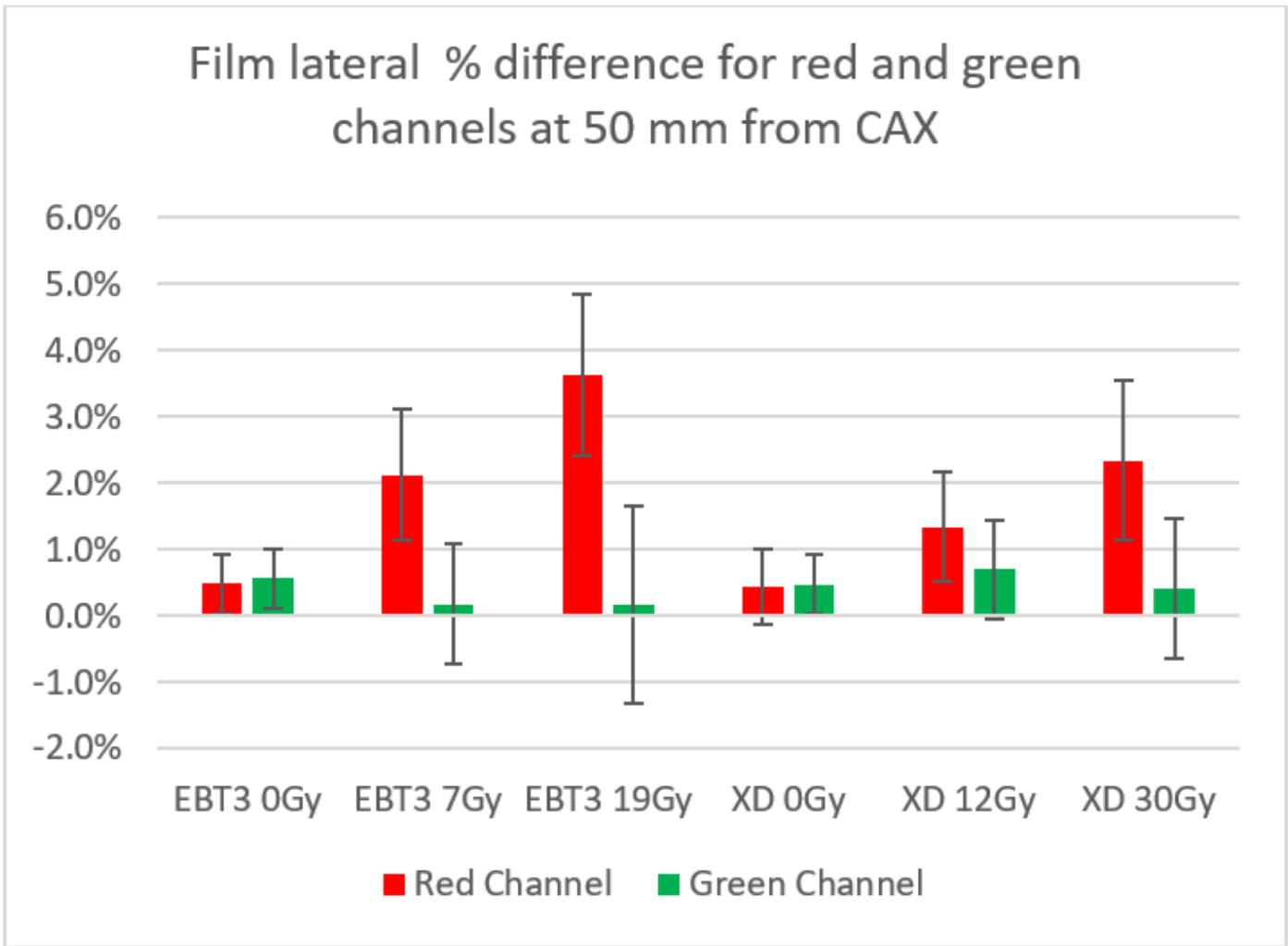
Figure 1

Patient in frameless QFix's Encompass™ with thermoplastic mask



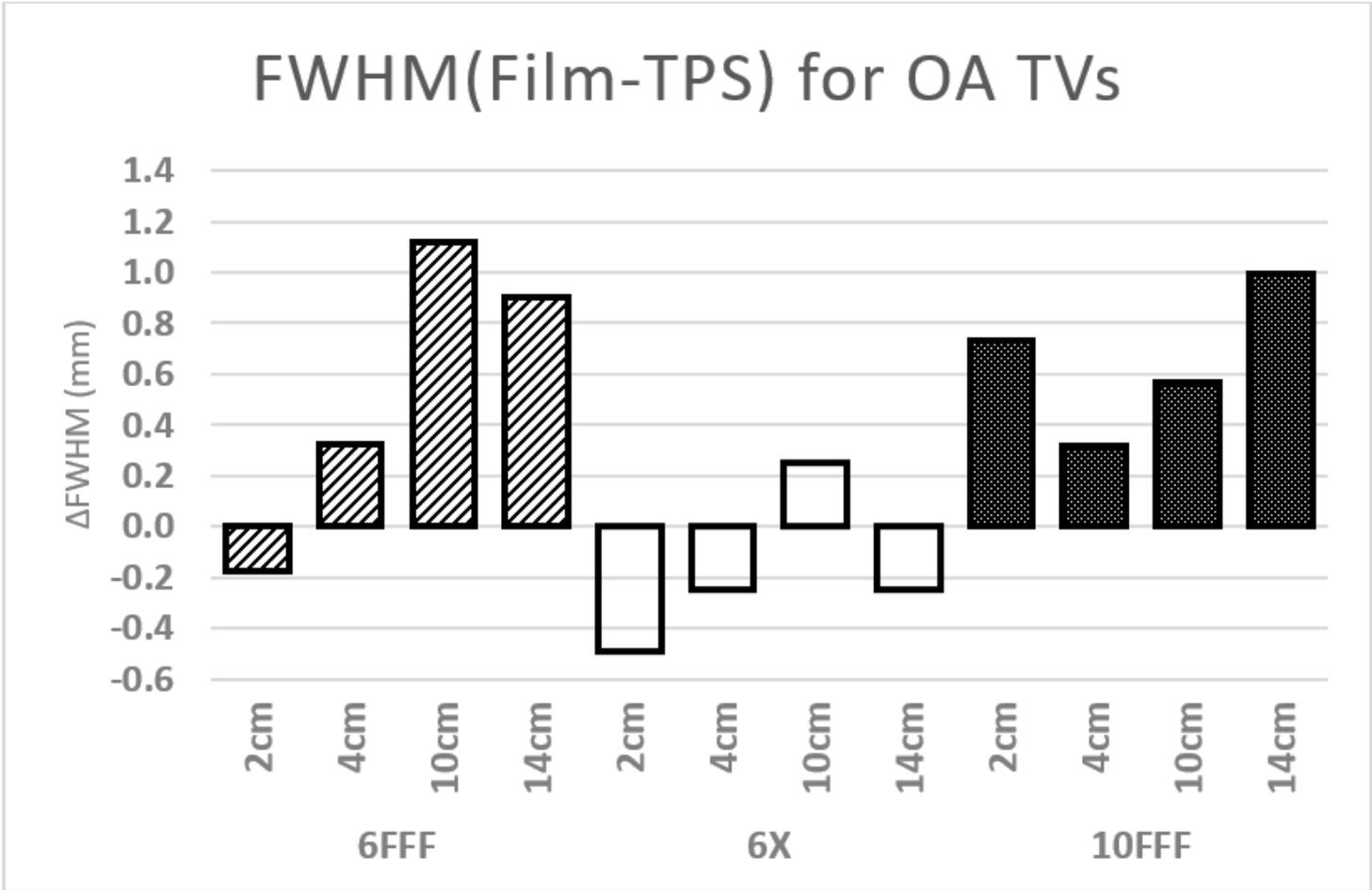
**Figure 2**

Multi-met plan delivered on film showing the fiducial markers designating the radiation isocenter. Dose wash from each of the arcs with couch kicks are just visible



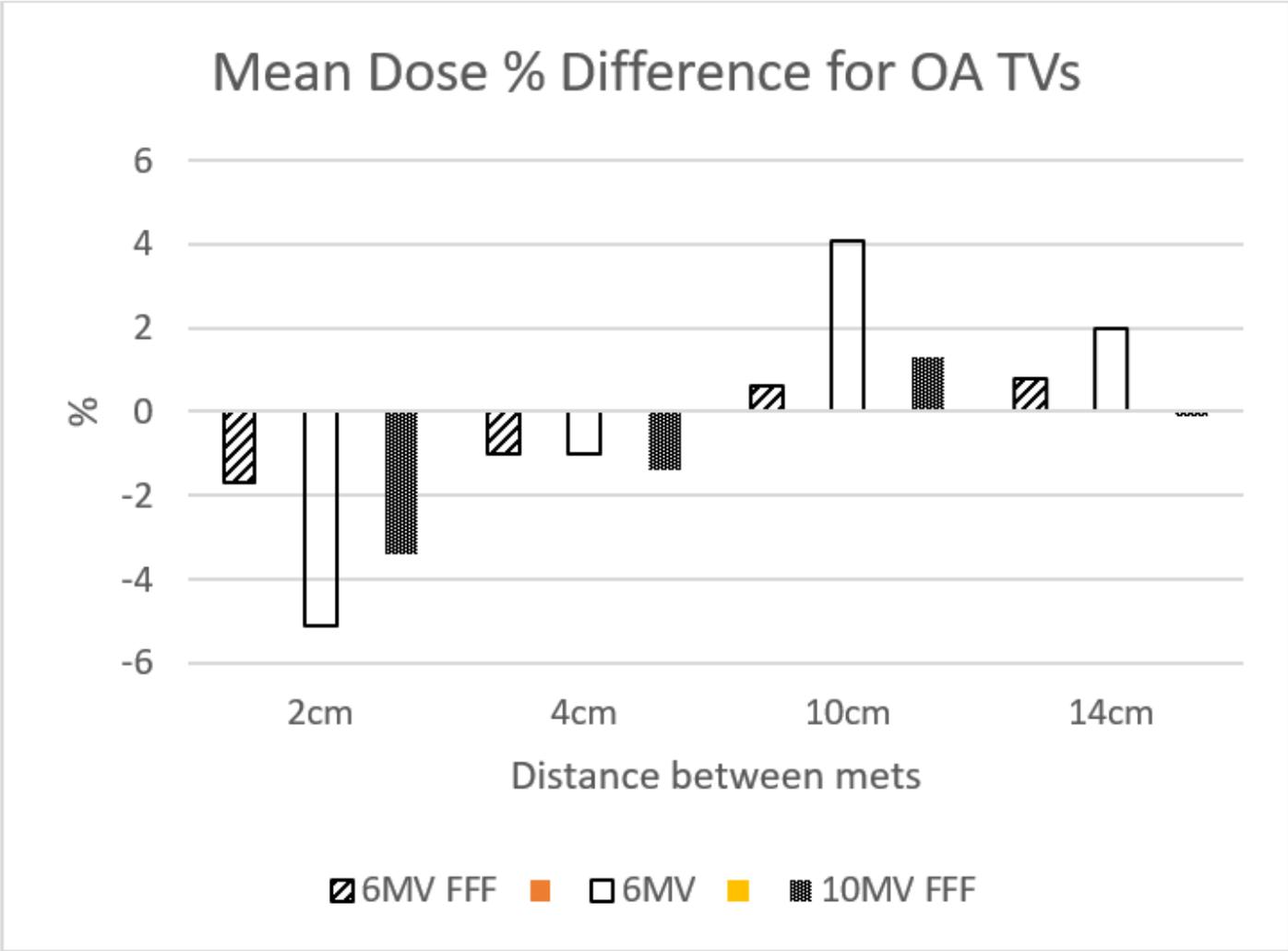
**Figure 3**

Dose variation across Epson 1100 XL scanner bed 50 mm from the central longitudinal axis for EBT3 and XD film for red and green channels with film measurement uncertainty.



**Figure 4**

FWHM difference between Film and TPS for 20 mm mets separated by distances of 2-14 cm



**Figure 5**

Mean dose percentage difference for OA TVs between film and TPS showing independence of axial distance up to 7 cm from isocenter.

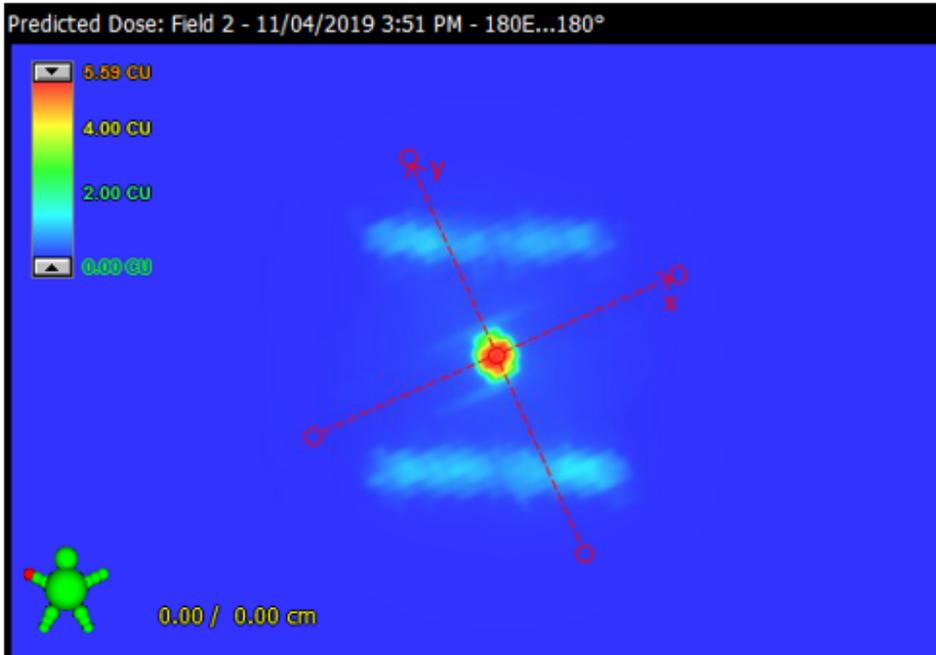
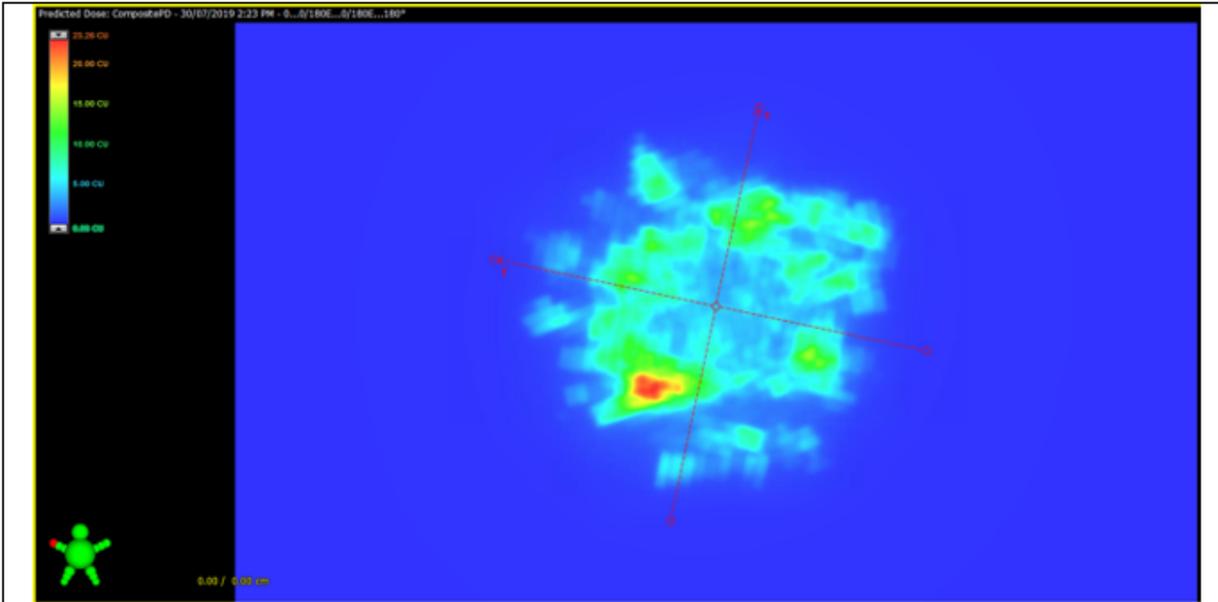
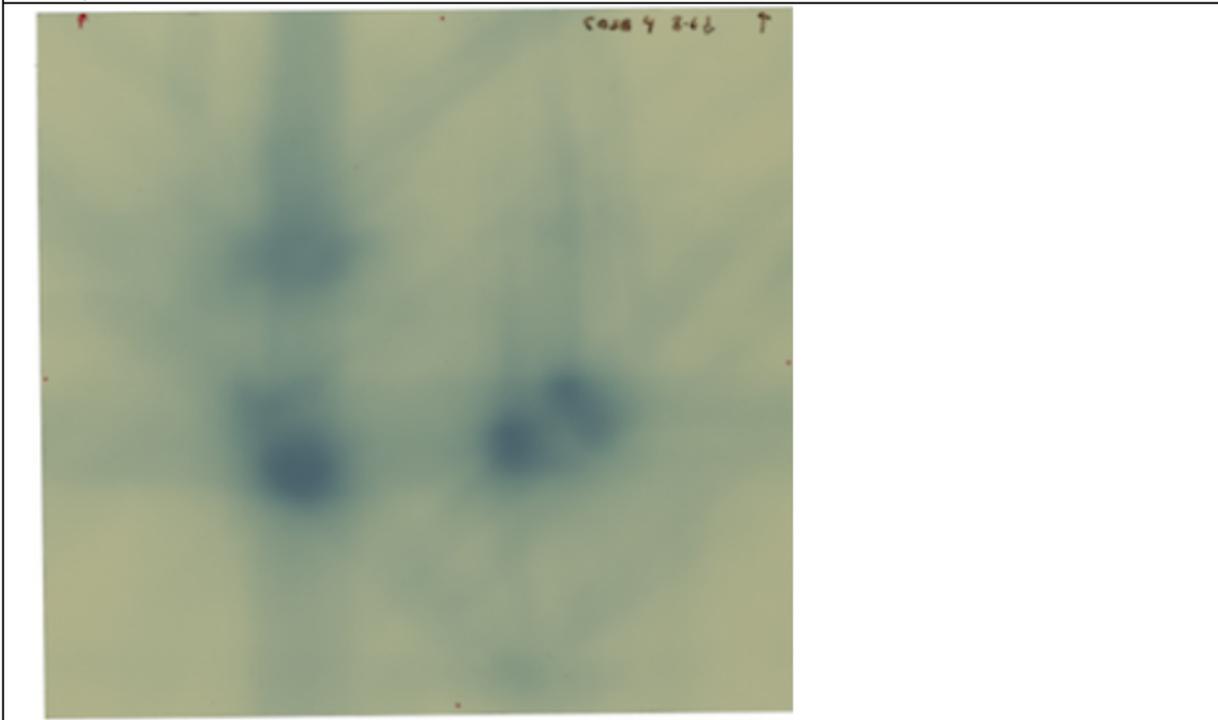


Figure 6

PDIP for a multi-met HyperArc plan showing defined TV at isocenter and two other OA TVs with no peak definitive peak dose



7a)



7b)

**Figure 7**

Case 4 brain mets showing a) the PDIP fluence map from the HyperArc plan for 12 mets, b) film fluence at a coronal plane 4 cm post from isocenter.