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Point dose verification of Cranial Stereotactic Radiosurgery using micro Ionization Chamber and EBT3 film for 6MV FF and FFF beams in Varian TrueBeam® LINAC

Gopinath MAMBALLIKALAM[a], S. Senthilkumar[b], Ahamed BASITH P.M.[c], Rohit INIPULLY[c], Jayadevan P.M.[c], C.O. Clinto[c], Jaon bos R.C.[c]

[a]*R & D, Bharathiar University, Coimbatore, Tamilnadu, India & Aster Medcity, Kochi, Kerala, India*
[b]*Rajaji Hospital & Madurai Medical College, Madurai, Tamilnadu, India*
[c]*Aster Medcity, Kochi, Kerala, India*
[*]*E-mail address: mgnmenon@gmail.com*

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Abstract

Introduction: Achieving high positional and dosimetric accuracy in small fields is very challenging due to the imbalance of charged particle equilibrium (CPE), occlusion of the primary radiation source, and overlapping penumbra regions. These factors make the choice of the detector for Stereotactic Radiosurgery (SRS) patient-specific quality assurance (PSQA) difficult. The aim of the study is to compare the suitability of EBT3 Gafchromic film against CC01 pinpoint chamber for the purpose of SRS and stereotactic Radiotherapy (SRT) dose verification.

Material and Method: EBT3 Gafchromic film was calibrated against Treatment Planning System (TPS) doses (1 Gy – 35 Gy). CC01 pinpoint chamber and EBT3 film was used to verify Patient-Specific point doses of 21 intracranial lesions each planned with Static, Dynamic Conformal Arc (DCA), and Volumetric Arc Therapy (VMAT) using Varian TrueBeam Accelerator 6MV Flattening Filter (FF) and 6MV Flattening Filter Free (FFF) beams. The lesion sizes varied from 0.4 cc to 2.9 cc. The lesions were categorized into <1cc, 1cc-2cc and 2cc-3cc.

Results: High variations in measured doses from TPS calculated dose were observed with small lesion volumes irrespective of the dosimeter. As the sizes decreased high uncertainty was observed in ion chamber results. CC01 was observed under-responding to film in small lesion sizes (<1cc), where nearly 50% of results under-responded in comparison with Film results. Film results were more or less consistent for static and DCA plans. Static and DCA plans were consistent passing more than 73% of the plans of the smallest lesion size category. VMAT showed very poor PSQA agreement for all three volumes (32.1% for <1cc, 14.3% for 2cc-3cc and 39.3% for 2cc-3cc). No significant difference was observed between 6MVFF and 6MVFFF beams from the chi-squared test.

Conclusion: EBT3 Film was observed to be a more suitable detector for small lesion sizes less than 1cc, compared to CC01. As the volume increases, the response of CC01 and EBT3 film have no significant difference in performing PSQA for intracranial SRS/SRT. VMAT techniques for intra cranial SRS shows deviation from TPS planned dose for both EBT3 film and CC01 and should not be preferred choice of verification tools.

Key words: patient specific quality assurance; stereotactic radiosurgery: EBT3 Gafchromic film, CC01 pinpoint chamber; flattening filter free photon beams.

Introduction

In stereotactic radiosurgery, an extremely high radiation dose is delivered to small targets in a single fraction. Achieving high positional and dosimetric accuracy in small fields is very challenging for a clinical medical physicist. There are mainly three techniques to deliver radiation dose; (a) multiple static conformal beams, (b) Direct Conformal Arc (DCA) and (c) Volumetric Arc Therapy.[1] VMAT technique is having in addition complex nature due to composite fields and inverse planning. It is important to verify radio-surgical absolute dose while using intensity modulation for SRS, because of its complex fields. Which detector is most suitable for patient-specific dose verification by considering the spatial resolution, dosimetric, and measurement uncertainty in IMRS (Intensity Modulated Radio Surgery), DCA and static beams turned to be the aim for our study. These small fields have high dose gradients, small spatial regions, and accompanying penumbra.[2] IMRT adds up small dose distributions in non-equilibrium conditions to treat large volumes using optimization routines.[3]

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Hence, uncertainty with beamlet-based treatment is a major concern when the width of the individual beamlet is smaller than 2 cm. Modern Linacs with HD MLC, 6D Robotic Couch, and Exactrac system is capable of delivering frameless cranial stereotactic radiosurgery.[1] Patient-specific dose verification is an integral part of SRS treatment, where a dosimeter or radiochromic film chamber is used to verify that the plan created in the Treatment Planning System (TPS) is executable within the permissible deviation of + or -3%.

The principles of radiotherapy physics are defined for a standard field size of 10x10 cm^2 where charged particle equilibrium has been satisfied. In small field dimensions, the physics is much different. The major differences in small field dosimetry include:

a) A major complication introduced in small field dosimetry is the imbalance of charged particle equilibrium (CPE), especially as the electrons traverse through low-density inhomogeneities.[4] The electrons from MV beam have a considerable range in water. The lateral range of electrons is a critical factor defining lateral charged particle equilibrium. Li et al has shown that the lateral range of electrons is energy-dependent.[5] As the energy increases the penumbra, where lateral CPE is not satisfied, widens.
b) The second issue is the comparable size of the treatment fields to the source dimensions. As a consequence of partial blocking of the source the entire field is composed of pronounced and overlapping penumbra.[6-8] As a consequence the output is lowered and apparent field widening occurs.[3]
c) The final issue is the finite size of the detector which may perturb the dose distribution.

All these factors make the choice of a suitable detector for SRS Patient-Specific Quality Assurance (PSQA) a difficult choice. Small lesions of 0.5 cc are common in SRS/SRT where extreme precision is required in planning and verification of the treatment plan.

Materials and Method

Ion chamber

The ionization chamber has been the backbone of dosimetry in medicine because the physics of the ionization chamber is well understood. The ionization chamber is stable, reliable, easy to calibrate, accurate, shows long term stability and linearity with dose, capable of infinite repeatability and also provide integral and instantaneous doses.[2]

Ionization chambers work on the basis of cavity theory. CPE has to be satisfied in order for cavity theory to work. Cavity theory assumes that:

- the introduction of the air cavity (chamber) does not perturb the medium,
- the dose is deposited only by crossers.[9]

SRS introduces small fields that may not satisfy Lateral Charged Particle Equilibrium (LCPE). The introduction of an ion chamber for dosimetry perturbs the local level of CPE further. This is a common occurrence in beamlet based intensity modulation and small fields for minute lesions, making dose verification a complicated process.

The introduction of the ion chamber changes the dose deposited and it can be corrected for in the following manner:

- Ion recombination, P_{ion}
- Replacement correction, P_{repl}
- Wall correction, P_{wall}
- Central electrode correction, P_{cec}
- Perturbation correction P_{pcf}[10]

$$Q(E,r) = Q_m P_{ion} P_{repl} P_{wall} P_{rec} P_{pcf} \quad \text{Eq. 1}$$

For large Fields (> 4x4 cm^2) where CPE is satisfied, the ratio of these corrections to the reference field cancels out. However, in the absence of charged particle equilibrium, these factors can be significantly different and need to be corrected.[11,12] The perturbation factors can become as high as 18% for 5 mm diameter circular field.[11] These corrections are significantly different in non-equilibrium conditions which are affected by the dimensions of the inserted chamber.[3]

The ionization potential of air (W/e) may depend slightly on the beam energy spectrum which may change with field size.[13,14] The stopping power (S/ρ) is energy-dependent and as the spectrum changes with field size for high energy beams, variations in stopping power cannot be ignored.[15-17] Since the reference field 10x10 is characterized by broad beam geometry with scatter contribution and small fields by narrow beam geometry, there may be a noticeable change in the spectrum of the fluence of x-rays and subsequent electrons entering the detector.

Escude et al. has observed that the variation between TPS calculation doses and measurement dose are in better agreement for pinpoint chambers than for larger chambers.[18] Koksal et al have found that the disagreement between measured and calculated doses for plans created by using collimators with small diameters was found the greatest. High dose gradient regions showed much variation in absolute measurements.[19] A commonly observed IMRT dose verification failure with ion chamber is the hot junction (usually 1-2 mm wide) in the split IMRT field for H&N patients.[2]

EBT3 Film

Ionization chambers are considered the gold standard of radiation dosimetry in medicine because cavity theories are well understood. However, when small fields come into picture cavity theory may breakdown due to lack of charged particle equilibrium at a high gradient region.

In the small field, where high precision is necessary, an alternative approach may be offered by Gafchromic films which offer the following advantages:

- Two-dimensional high-resolution dosimetry in high dose gradient regions. The greatest advantage of gafchromic films is the high spatial resolution of >1200 lines/mm or 25 µm.[20,21]
- Thinness (**Figure 1**) and near water equivalence, which prevents perturbation of electronic fluence in high gradient regions.
- Low spectral sensitivity.[1] The sensitive layer of the Gafchromic films has very close mass energy absorption coefficient (μ_{en}/ρ) and Stopping power (S/ρ) to that of water and skeletal muscle which makes this detector water equivalent.[22] The ratios of (μ_{en}/ρ) and (S/ρ) from gafchromic to water is within 3%. Other detectors such as TLD, semiconductors, and the radiographic film showed much difference in water equivalence to water.[23] Experimental studies have shown that X- and gamma rays have no appreciable energy dependence for a dose to water.[24,25]

These features of the film may prove film to be superior to pinpoint chambers in very small lesions, especially for volumetric fluence modulation techniques, where overlapping penumbral regions may be a challenging aspect for ion chambers.[2]

The film comes with certain disadvantages.

- The primary one being that the film requires a certain period of delay before readout to allow for polymerization; Current film protocol requires 15-24 hour delay between irradiation and readout of the film.
- Noise and accuracy. Batch film calibration is required, which is performed using a calibrated ion chamber. Multiple films are required to yield uncertainties less than 1%.[2]

Image formation in radiochromic films occurs as a polymerization process of photo-monomers when energy is transferred from either photons or electrons. These films are self-developing and do not require latent chemical, optical or thermal development. Radiochromic dosimeters are available in various forms such as thin film, thick film, liquid solution, gel, and liquid core waveguide. These dosimeters have a range from 10^{-2} to 10^{6} Gy and can be used for high dose rates up to 10^{12} Gy/s.[26] The recent improvements in the production of rugged and easy to use radiochromic films have increased the popularity of gafchromic films.

Method

The experiment was performed under Varian TrueBeam Accelerator 6MV FF and 6MV FFF beams. 21 intracranial lesions of sizes <1 cc, 1cc - 2cc, and 2cc - 3cc (7 each) were used for this study. Treatment plans for these lesions were created for both beams using Static, Dynamic Conformal Arc (DCA) and Volumetric Arc Therapy (VMAT) in the Eclipse planning system using Anisotropic Analytical Algorithm (AAA, version13.7) and the dose calculation grid used is 1 mm.

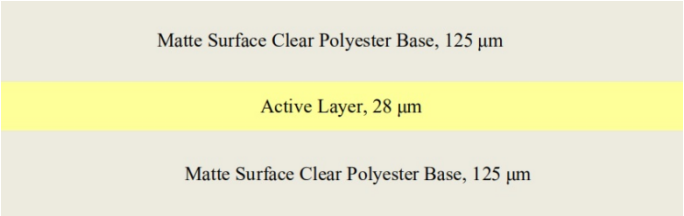


Figure 1. Structure of Gafchromic EBT3 film.[20]

Total 252 PSQA plans were created for 21 lesions for all the three modalities with FF and FFF beams and for CC01 and EBT3 film. An IBA RW3 phantom was replaced in the PSQA plan, with beam configurations unchanged.

Each of these PSQA plans was tested with the ionization chamber and EBT3 film SAD (100 cm). The CC01 chamber was placed in the RW3 phantom adapter plate with 5 cm build up and 10 cm backscatter plates. Electrometer used was an IBA Dose1 electrometer. The percentage deviation of the dose measured was calculated against the dose estimated from the treatment planning system. The film measurements were performed in a similar manner, with 5 cm build up slabs and 5 cm backscatter slabs.

Gafchromic EBT3 film from Ashland was used for PSQA. The EBT3 film is symmetrical and the Newton ring coating has been provided. The scan direction is still an affecting factor, i.e. scanning along with the longer and shorter dimension may give different results. The film orientation was marked on every piece of film cut-out with an arrow facing the right-upper-most corner of the big film and the orientation of the film on the scanner bed was in such a way that film gets scanned along its shorter dimension. The scanner used for this dosimetry project was Epson Expression 10000XL, the scanner that Ashland recommends for Gafchromic films. The central region of the scanner was used for all scans to avoid Lateral Scan Artefact.[27] The film was placed in this orientation at the centre of the scanner bed with the help of the external markers on the scale on scanner bed edges. Pre-exposure scan was taken for all measurements to have the background measured and scan settings were 300 dpi, 48 bit Color with no color correction in transmission mode. The post-exposure scan was performed after 24 hrs, after which optical density development is very insignificant for EBT3 film. The images were all saved in the TIFF (Tagged Image Format) which is accessible with Omnipro software and ImageJ software.

Gafchromic film was calibrated against TPS calculated doses ranging from 1-30 Gray for an open field at 5cm depth and 5cm backscatter in RW3 phantom. Green channel was used for scanning at doses above 6-8 Gy as this does not saturate at high doses.[28] The measured pixel values from post-irradiated and pre-irradiated film were used to find the optical density of each of the film.[29] The optical densities, thus obtained, were plotted against the TPS doses to obtain calibration curve for film dosimetry (**Figure 2**).

$$OD = \log_{10}\left(\frac{\text{Pre-Irradiation Pixel Value}}{\text{Post-Irradiation Pixel Value}}\right) \quad \text{Eq. 2}$$

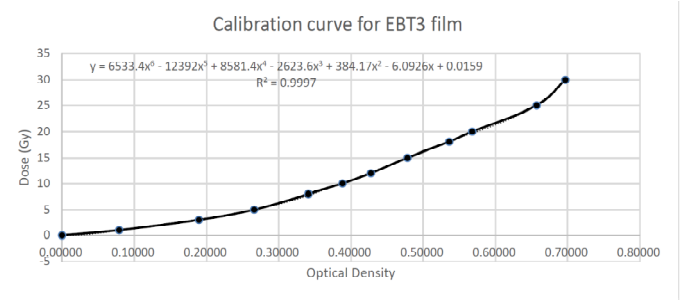
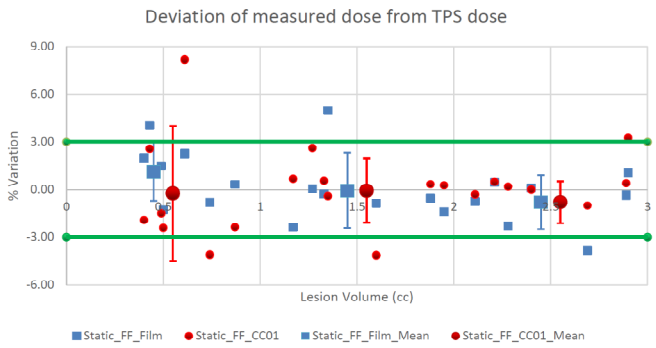


Figure 2. Optical densities plotted against Doses. The figure also shows the polynomial curve fitting equation of 6th order obtained.

Results

PSQA for 252 plans were performed using Gafchromic film and CC01 pinpoint chamber in RW3 solid phantom for tumor volumes varying from 0.4 cc to 2.9 cc. The volumes were categorized into three, <1cc, 1cc-2cc and 2cc-3cc. The dose measured in either EBT3 film or CC01 pinpoint chamber was considered to be in agreement if the measured dose was within ± 3% of the TPS calculated dose. PSQA results for Static, DCA, and VMAT using CC01 and Film for 6MV FF and FFF beam are plotted in **Figures 3a** and **b**, **4a** and **b** and **5a** and **b**.

a)



b)

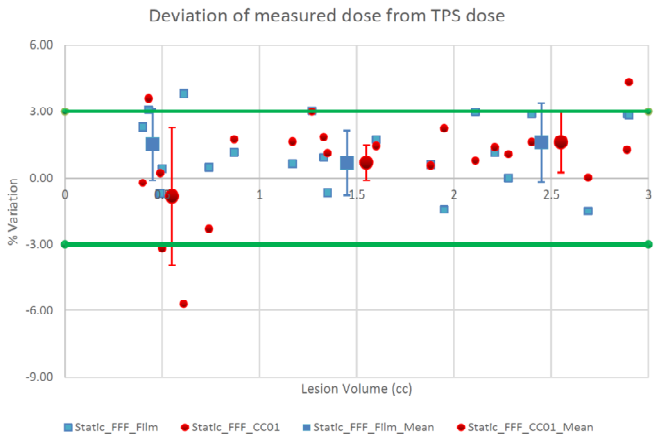
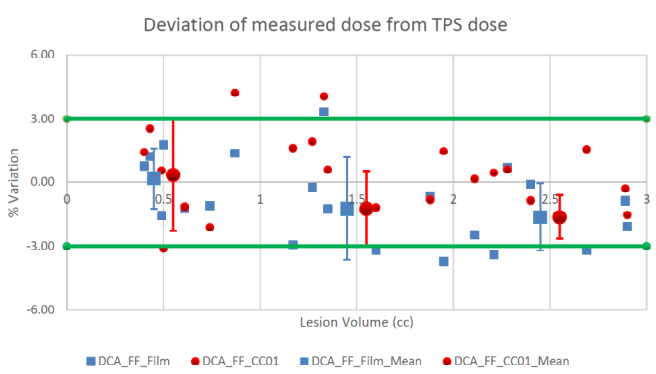


Figure 3a and b. Deviations of measured dose from TPS dose for each lesion volume is plotted in the figure above. The plotted data points include Static PSQA results from Film and CC01 for 6MV FF and FFF beams. Mean value and standard deviation of each volume category is plotted, which can be identified by enlarged data point and error bar. The chamber was seen to be inconsistent around the proximity of 1cc volume. CC01 was observed to be highly reliable for PSQA for lesions sizes above 2cc which is evident from other figures as well.

a)



b)

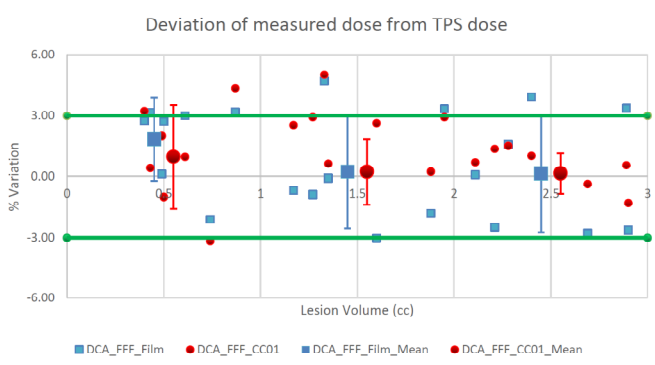


Figure 4a and b. Deviations of measured dose from TPS dose for each lesion volume is plotted in the figure above. The plotted data points include DCA PSQA results from Film and CC01 for 6MV FF and FFF beams. Mean value and standard deviation of each volume category is plotted, which can be identified by enlarged data point and error bar.

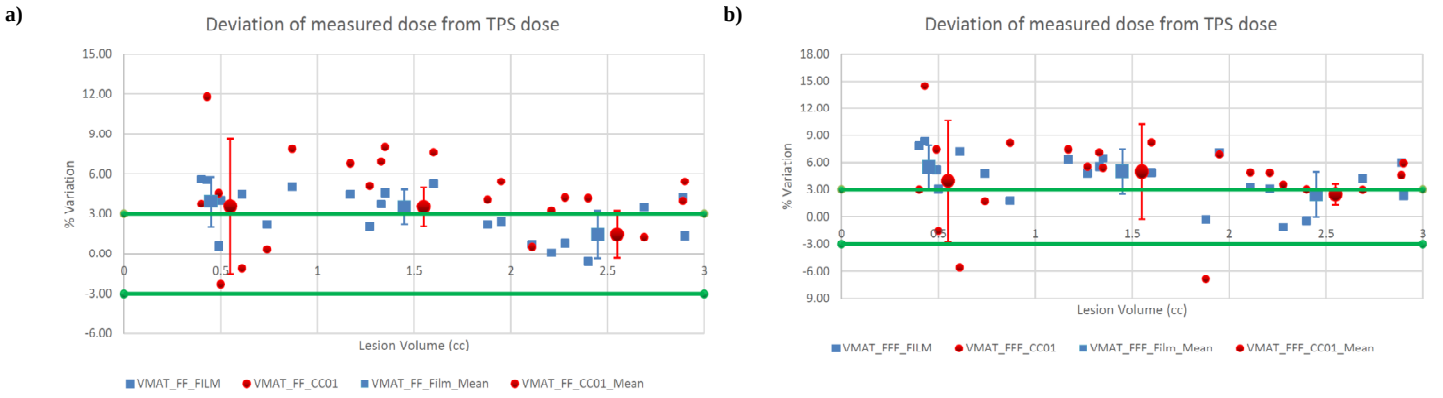


Figure 5a and b. Deviations of measured dose from TPS dose for each lesion volume is plotted above. The plotted data points include VMAT results from EBT3 Film and CC01 for 6MV FF and FFF beams. In comparison to the Static and DCA results, VMAT PSQA results are very poor for film and CC01 chamber.

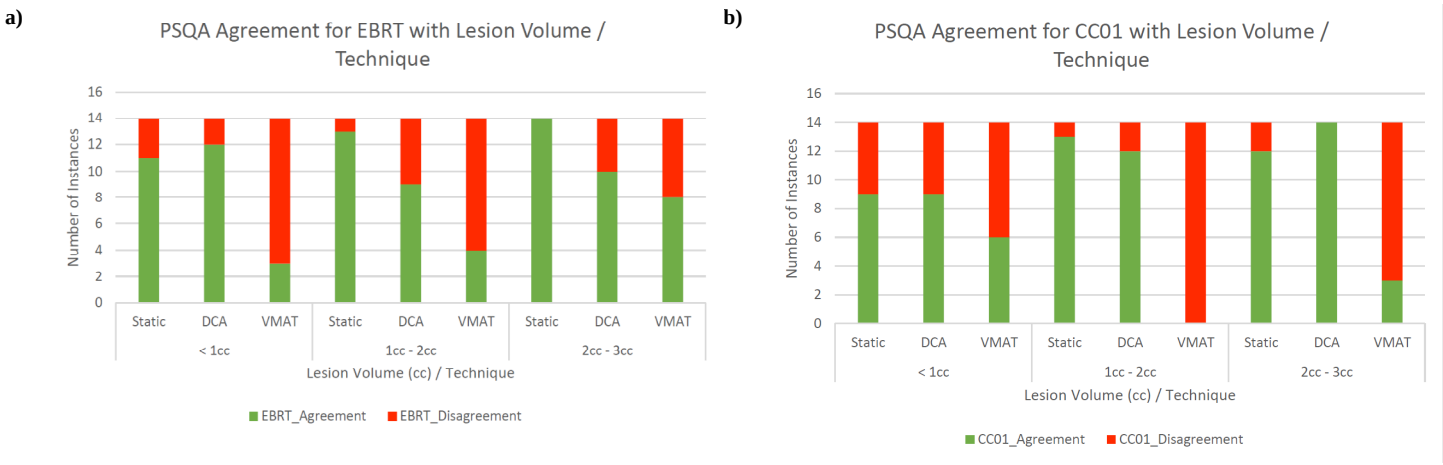


Figure 6a and b. PSQA agreement as a function of lesion volume treatment plan technique for EBRT3 film and CC01 is plotted below.

Table 1. PSQA passing percentages for all lesion volume categories and different techniques

Volume	Technique	Film		CC01		Total	Agreement Percentage (%)	Average Agreement %	Agreement Static+DCA(%)
		Agreement	Disagreement	Agreement	Disagreement				
< 1cc	Static	11	3	9	5	28	71.4	59.5	73.2
	DCA	12	2	9	5	28	75.0		
	VMAT	3	11	6	8	28	32.1		
1cc - 2cc	Static	13	1	13	1	28	92.9	60.7	83.9
	DCA	9	5	12	2	28	75.0		
	VMAT	4	10	0	14	28	14.3		
2cc - 3cc	Static	14	0	12	2	28	92.9	72.6	89.3
	DCA	10	4	14	0	28	85.7		
	VMAT	7	7	4	10	28	39.3		

PSQA passing ratios for each lesion volume category and technique are tabulated and plotted below in **Table 1** and **Figure 6**. PSQA from Static and DCA showed high levels of agreement with more than 70% in agreement for the smallest lesion volume of <1cc. The lowest agreement in <1cc volume category was 71.4% (20 out of 28) for static plans. DCA was slightly superior at 75.0%. As the lesion volume increased static plans showed superior PSQA agreement at 92.9% for 1cc-2cc and 2cc-3cc categories. DCA showed 75% agreement for 1cc-2cc and 85.7% for 2cc-3cc. VMAT showed very poor PSQA agreement for all three volumes (32.1% for<1cc, 14.3% for 2cc-3cc and 39.3% for 2cc-3cc). All three techniques showed better PSQA agreement with TPS calculated dose as the tumor volume increased. Overall agreement (average of Static, DCA, and VMAT) was also seen improving with lesion size, however, the inclusion of VMAT brings down the passing ratio.

Table 2. The comparison between CC01 and film PSQA results are listed in the table. CC01 results can be seen to under-respond in comparison with film results for lesion sizes <1cc.

Volume (cc)	CC01 Under-Response		Agreement b/w CC01 & EBT3		CC01 Over-Response	
	Instances	Percentage (%)	Instances	Percentage (%)	Instances	Percentage (%)
<1cc	20	47.6	15	35.7	7	16.7
1cc-2cc	3	7.1	28	66.7	11	26.2
2cc-3cc	1	2.4	31	73.8	10	23.8

The comparison between CC01 and film PSQA results was performed using the difference between the percentage deviations of each PSQA from the TPS dose. Differences between CC01 and film within ±3% were taken as an agreement between the two detectors. Differences of CC01 from film greater than 3% were taken as over-response and less than -3% were taken as under-response. The ionization chamber showed under-response in doses with respect to film doses for small lesion volumes <1cc as can be seen from **Figure 7**. 20 out of 42 PSQA performed with CC01 showed under-response (**Table 2**). The 20 under-responding PSQA results revealed that the chamber showed an average under-response of -4.1% from EBT3 film. 18 of the CC01 PSQA were less than 10% below film deviations. 2 results (12.8-%, -14.1%) showed under-response greater than 10%. The agreement between CC01 and film was as low as 35.7% (15 PSQA out of 42) for small lesion volumes <1cc. The over-response is 16.7% (7 PSQA), with a maximum at 6.27% above film. The average difference between CC01 and film was only -1.15%, however, the standard deviation in the difference was as large as 5.19%. For lesion volumes between 1cc and 2cc the under-response was as low as 7.15% (only 3 PSQA results, -5.4%, -10.1%, -6.6%) and 66.7% results (28/42 PSQA results) were seen in agreement with each other. 26.2% (11 PSQA results) showed over-response, with the maximum difference at 5.7%. The average difference of CC01 from film was +1.26%, with a standard deviation of 2.91%. For the largest lesion sizes used in the study 2cc-3cc, the agreement between CC01 and film was the highest at 73.8% (31/42 PSQA results). Only 1 PSQA (-3.79% under-response) showed under-response in this lesion size category. 23.8% of the results (10 PSQA) of CC01 showed over-response from film results. 4.8% is the maximum difference of CC01 PSQA result from the film. The Average difference between CC01 and film was +1.12% and the standard deviation was 2.15%.

The comparison between the PSQA results for 6MV FF and FFF was performed using statistical analysis in IBM SPSS Statistics (v20). The PSQA results were categorized into 0 - ±3%, ±3 - ±7%, and > ±7%. The test used for statistical analysis was Pearson's Chi-squared for 2 degrees of freedom. For the given degrees of freedom (2) no PSQA results gave p-value < 0.05%. Hence, there is no statistical difference between 6MV FF and FFF PSQA results at a 95% confidence level (**Table 3**).

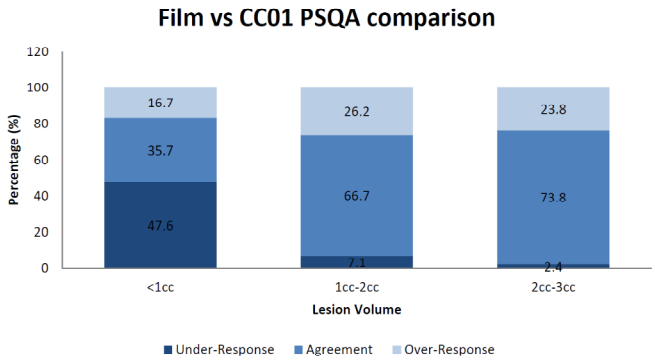


Figure 7. The response of IBA CC01 chamber in comparison with Ashland EBT3 Gafchromic film.

Table 3. χ2 test P-value for various detectors and techniques.

Dosimeter	Film			CC01		
Technique	Static	DCA	VMAT	Static	DCA	VMAT
P-value	0.344	0.546	0.3	0.834	0.231	0.927

Discussion

The point dose measurements performed in EBT3 and CC01 for PSQA showed large variation for various treatment techniques. It was observed that the maximum overestimated and maximum underestimated point dose measurements decreases with increasing lesion volume category. The same trend was seen for the standard deviation of point dose measurements. Film PSQA for static and DCA beams were very consistent. CC01 results can be seen to show wide variations are lesion size reduced. Static and DCA PSQA showed high levels of agreement, which improved as the lesion size increased. VMAT PSQA results were very inconsistent irrespective of the detector used. PSQA for VMAT plans showed very poor results even for the highest lesion size category (2cc-3cc) used in this study passing only 39.3% of plans. The average passing percentage was only 28.6% whereas the average passing rate for static and DCA combined was 82.1%. Since VMAT fields are composed of small beamlets modulating fluence to produce overall dose distribution the accuracy of the planning algorithm is very critical.

Comparison of CC01 with EBT3 film showed under-response in small volumes <1cc. The output factor of CC01 has been published and has been shown to under-respond steeply below 2x2 cm^2.[30] This has been clearly observed in the results of this study, where nearly 50% of PSQA results for CC01 under-responded in comparison with Film PSQA. As the lesion size increased the agreement between the two detectors was seen to improve. For larger lesion sizes between 2cc-3cc the agreement was at 73.8%. Furthermore, the absence of charged particle equilibrium in small fields and beamlet based IMRT also makes CC01 ionization not necessarily proportional to the dose distributed in the area due to perturbations.[30] About 15-25% of the CC01 PSQA results showed over-response against Film irrespective of lesion size which may have been caused due to perturbations in electronic fluence. A clear indicator of the increasing agreement between the two detectors is seen in the decreasing standard deviation with volume size (5.19% for <1cc, 2.91% for 1cc-2cc, 2.15% for 2cc-3cc). The film showed the most promising PSQA results for Static and DCA treatment plans. There is no statistical difference between 6MV FF and FFF PSQA results at a 95% confidence level.

Conclusion

The overall PSQA results observed from film and CC01 chamber showed wide deviations from TPS calculated doses. However, the breakdown of various factors showed the deviations are dependent on the detector of choice, the lesion volume, and the treatment technique. The film was observed to be superior to CC01, especially for small lesions sizes.[28] Under-response of CC01 chamber in small volumes was noticeable.[31,32] Static and DCA plans were more consistent than VMAT. Neither Film nor CC01 showed promising PSQA results for VMAT plans. The only scenario where VMAT is the planning choice may be for highly irregular lesion volumes adjacent to a critical structure. Between Static and DCA there were no considerable differences observed dosimetrically. The film was observed to be more suitable for lesions sizes <1cc. The under-response of CC01 in small lesions is nearly 50% in comparison with the film. There was no significant difference between the results of 6MV FF and FFF beams. There was no energy dependence observed in this study. Overall, for small lesions, either static or DCA plans with EBT3 film as preferred dosimeter should give the highest chance of successful Patient-Specific Quality Assurance.

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