Pre-clinical and small field dosimetry

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Abstract. Preclinical in vivo studies have drastically improved over the past decade with the development of cone beam computed tomography (CBCT) image-guided small animal irradiation systems. Such systems produce 220 or 225 kV x-rays with square and circular field sizes ranging from 0.5 to 10 mm. The dosimetry of such equipment involving kilovoltage small-field dosimetry has not received as much attention as the megavoltage small-field dosimetry. The dosimetry of megavoltage small fields can be challenging due to lateral charged particle disequilibrium, detector volume averaging effect, and high dose gradients. Clinically there has been a rapid increase in the use of small fields in modern radiotherapy techniques such as stereotactic radiosurgery (SRS) and stereotactic radiotherapy (SBRT). This study presents dosimetric properties of image-guided small animal irradiation systems. Both EBT Gafchromic films and 3-D PRESAGE measured beam data were presented and compared with the calculated dose distribution from a commissioned planning system. For megavoltage small-field dosimetry, EBT3 films and PRESAGE dosimeters were used to measure the dose distributions for MLC-delimited 6 x 6 to 20 x 20 mm² square fields, and for selected IMRT and VMAT plans with small field sizes or segments of 1-4 cm. A single-beam optical CT scanner was used as the readout mechanism of the radiation-induced 3-D information in the PRESAGE phantoms. Measured data sets were compared with calculated results from Eclipse Acuros XB. The results for kilovoltage small animal irradiator showed that PDD data measured from EBT films and PRESAGE dosimeters are in agreement within 3%; profiles and 2-D dose distributions measured from PRESAGE present a larger penumbra compared with those from EBT films. Discrepancies between measured beam data and treatment planning data were identified. For megavoltage small fields, the measured data percent depth dose, beam profiles, and dose distributions were found to agree within experimental uncertainties for EBT films and PRESAGE dosimeters. Beam profiles for MLC-delimited field sizes less than 10 mm reveal some discrepancies in the penumbra region between measured data and calculated results. Dose distributions from EBT film and PRESAGE measurements demonstrate that 3-D dosimetry measurement for small-field IMRT and VMAT QA may be necessary to ensure a complete verification of dose delivery and accuracy.

1. Introduction
The development of modern radiotherapy techniques in the past 20 years have been driven largely by the advances in technology and physics. In cancer research, small animal studies are commonly used to assess the effectiveness of radiotherapy, test hypotheses concerning radiation-induced effects, and define the genetic underpinnings of specific cancers. The recent development of image-guided small animal irradiation platforms, the Xstrahl Life Sciences (Camberly, UK), Small Animal Radiation Research Platform (SARRP) and the Precision X-ray Inc. (North Branford, CT), X-RAD 225 Cx, has
enabled the translation of animal-based in vivo radiation research into clinic. Both systems are offering CBCT image-guided precision irradiation, bioluminescence tomography, and treatment planning systems with dose calculation tools based on superposition convolution model (Muriplan from Xstrahl) or Monte Carlo calculation (SmART-Plan from Precision).

While this system is still under improvement to better simulate the capability and functions of modern radiotherapy equipment, a precise commissioning procedure is essential in order to maintain an accurate imaging and beam delivery. However, there are two major physical properties that are inherently challenging: (a) small radiation field dosimetry (0.5 mm to 10 mm) and (b) kilo-voltage x-ray energies (220 kVp for SARRP and 225 kVp for X-RAD 225Cx). Small field dosimetry is challenging due to the lack of charged particle equilibrium and the size of detectors commercially available, often resulting in partial chamber volume exposures, causing an underreporting of beam output. Additionally, kilo-voltage energy presents a dosimetric challenge due to the significant dose gradient over the volume of measurement device in addition to variance in the dose response of the materials used [1]. To overcome these challenges multiple sets of EBT film, 3-D PRESAGE dosimeters, and Monte Carlo approach have been used for commissioning dosimetry data by several groups [2-5]. These research studies demonstrate that kilovoltage small field dosimetry is more susceptible to measurement uncertainties than megavoltage beams. Recently, Na et al described a process of evaluating the mechanical and dosimetric characteristics of SARP utilizing a Farmer type ionization chamber, EBT3 films, and PRESAGE dosimeters. In addition, Wang et al have demonstrated that EBT3 films, with optimized protocols, can be used to acquire accurate and precise beam data of small animal kilovoltage x-ray irradiator with fields down to 0.5 mm. They have also verify the calculated beam data and dose calculation from the Muriplan with measured data and Monte Carlo simulated data. This allows investigators to image an animal by CBCT, plan the treatment and complete dose delivery in one session of anesthesia.

Modern radiotherapy such as stereotactic radiosurgery (SRS) and stereotactic body radiotherapy (SBRT) using intensity modulated radiation therapy (IMRT) or volumetric modulated radiotherapy (VMAT) may have relatively small fields (5 mm to 3 cm) to achieve desired dose distribution. An accurate dose verification of small-field treatment delivery is therefore crucial. The measurement of small-field beam data, including output factors, percentage depth dose (PDD), and lateral beam profile, is required for the commissioning of treatment planning systems. However, the dosimetric characterization of small fields is difficult due to the potentials for lateral charged-particle disequilibrium, partial source occlusion with the consequence of reduced output, and partial volume averaging effects [6]. Typical dose verification and end-to-end test for clinical treatment units uses a combination of point dose verification (ion chambers and solid state detectors) and planar isodose distribution comparison (radiochromic films) [7-9]. International atomic energy commission (IAEA) Report No. 398 provided a technical approach to deal with the issues in small field dosimetry. AAPM also formed a task group (TG-155) to set up recommendations for relative dosimetry in small fields [10]. However there is no guidance provided for small-field dosimetric measurement using 3-D dosimeters. 3-D gel and PRESAGE dosimeters can be used for accurate dose verification for modern radiotherapy techniques with high precision and spatial resolution [11-12], but require an extensive setup and specialized handling to maintain a sub-percent reproducibility. As such, they still need to be thoroughly investigated, characterized and benchmarked against other detectors [6].

3-D gel and radiochromic plastic dosimeters using MRI imaging or optical CT scanners as readout systems [13-15] have been utilized to measure dosimetric parameters from small-field megavoltage x-rays produced by linear accelerators. However, these studies were focused on measurements of output factors, percentage depth dose curves, and lateral beam profiles of small circular or square fields generated via cones or collimators [16-19]. Currently IMRT and VMAT QA were performed using ion chamber or diode arrays because of their ease of use and reliability. Comparison of the dose distribution measured in a phantom with the dose distribution calculated by the treatment planning system for the same experimental conditions is one of the routines for patient specific IMRT/VMAT QA. For the specific problems encountered in treatment planning of complex radiotherapy techniques such as the
use of small fields/segments and of dynamic delivery systems, additional tests are required to verify the accuracy of dose calculations for those conditions specific for small fields. For instance, for the high dose gradient in a small irradiated volume, should the dose distribution be verified in one plane, in several planes or the total 3D dose distribution? The main disadvantage of a 2-D detector arrays is that they do not offer full 3-D dose information and the detector spacing is too large (7 mm) for small field dosimetry [20]. Gel and radiographic PRESAGE dosimetry is the most commonly reported technique for full 3-D IMRT/VMAT QA [11, 21]. However, detailed full 3-D dose verification for small-field IMRT and VMAT radiotherapy has not been reported in the literature.

In this study, we demonstrate that an accurate and precise measurement of small-field 3-D dose distribution can be obtained using radiographic PRESAGE dosimeters in conjunction with a single-beam optical CT scanner. Dosimetric data of PDD, lateral beam profiles, and isodose distributions for small field sizes of 6 mm to 2 cm, delimited by MLC, were obtained from PRESAGE measurements and compared with those calculated from Eclipse Acuros XB. Comparison of dose distributions for selected IMRT and VMAT plans with small fields (1 - 4 cm) were performed between PRESAGE measurements and calculations from Acuros. Radiochromic film has probably the highest intrinsic resolution of detectors which are relatively water equivalent [22]. However, film requires specific protocols to obtain acceptable accuracy for reference dosimetry. It is very suitable for lateral profile and 2-D dose distribution measurements. For comparative dosimetry, we also present corresponding measurements with EBT3 radiochromic films.

2. Materials and methods

2.1. Image-guided small animal irradiation

All irradiations presented in this study were performed using the SARRP system, produced by Xstrahl. This platform incorporates CBCT imaging with precise radiation delivery, enabling researchers to target anatomical structures and confidently deliver photon beams with small field sizes to a specific point. Through different setups, this machine can provide two modes of operation: CBCT imaging and therapeutic irradiation. In the mode of CBCT imaging, the unit operates at 60 kVp at 0.5 mA with 1 mm Al filtration without collimation. For therapeutic irradiation, the setup is 220 kVp at 13 mA current with 0.15 mm Cu filtration. The SARRP has a source-to-isocenter distance of 35 cm and a number of fixed cone field sizes available for use. Like most of the treatment machines used clinically, a laser alignment system with millimeter accuracy is provided to support visual setup.

2.1.1. Dosimetric commissioning for SARRP

Irradiations to EBT3 films and PRESAGE phantoms were conducted for preclinical small-field dosimetry. Since EBT3 films came into clinical use, a large amount of research has been conducted to determine film characteristics and provide optimal protocols for dosimetry in the megavoltage X-ray energy range [23-25]. This is mainly due to increased demand in radiation oncology for IMRT and SRS treatment modalities. In contrast, only a small number of studies have been published aiming at providing guidelines for the dosimetry in the kilovolt energy range [3]. To acquire beam data of the small animal irradiator, PDD curves, beam profiles, and dose distribution of five field sizes were measured by films with 33 cm source to surface distance (SSD).

This study presents two methods of film measurement, axial film measurement and vertical film measurement. For axial film measurements, the film was stacked axially between 6 x 6 x 0.5 cm³ plastic water sections and then fixed to a commissioning jig to be irradiated using fixed collimators. The film was oriented perpendicularly to the beam direction at various depths. In contrast, for vertical measurements, film PDD curves were obtained through vertical parallel alignment to the beam central axis, held in the center of a 6 x 6 x 2 cm³ block of plastic water. A commercial Epson Expression 11000XL flatbed scanner was used for readout of irradiated EBT3 radiochromic films at 300 dpi resolution.
In the whole process of film measurement, the film digitization was the largest source of uncertainty. The error comes from (1) inappropriate scanning resolution, (2) scanning location dependence, and (3) developing time (time period between beam delivery and film scan). Therefore, it is important to optimize the protocol for film scanning to minimize these sources of error. For film measurements, a scanning resolution of 300 dpi was used to measure all the beam data while 150 dpi was used for the HD Curve generation. Resolution higher or lower than 300 dpi provided noisier or inaccurate results of small field measurements. To further minimize scanning error, the location of films on the scanner should be consistent for all measurements. The analysis of location dependence of our scanner, an EPSON 11000XL, shows a 5% difference between two films separated by 4 cm on the scanning bed. Finally, developing time of the films can significantly influence results. Therefore, an experiment was performed to find the optimal time for scanning. Films were irradiated by 8 different doses, 1, 3, 5, 7, 9, 11, 13, and 15 Gy, and each of the films was scanned at 6 different times, 0.5, 1, 2, 5, 24, and 48 hours after irradiation [3].

In addition to EBT3 film, cylindrical PRESAGE dosimeters of 6 cm height and diameter were used for the evaluation of beam characteristics. Commissioning data for 3 x 3 and 10 x 10 mm² fixed field sizes are used for this purpose. Each of the PRESAGE dosimeters was placed along the central axis of the beam, which is perpendicular to the gantry rotation axis, with guidance of crossed lasers. The readouts of irradiated PRESAGE dosimeters were performed with a single laser beam optical CT scanner. For scanning the irradiated PRESAGE dosimeter is mounted on the base of the scanner rotation stage. The tank is filled with optical refractive index matching fluid to match that of the PRESAGE dosimeter. A total of 1200 projection images per axial plane were used for 3D dose reconstruction. A filtered back projection algorithm was used to reconstruct the 3D dose map. The scanner can reconstruct a transverse image to a spatial resolution of 0.1-1 mm depending on the phantom size. Although the entire readout takes 6-10 hours, as a fundamental standard of OCT in 3D dosimetry, the single laser scanner produces consistent high quality results. From the reconstructed images, PDD curves, dose distributions and transverse profiles were obtained.

The PRESAGE-measured beam data was validated using both axial and vertical film measurements. The density of the PRESAGE used in this study is 1.07 g/cm³. Since the relative electron density of PRESAGE to water is 1.05, we have corrected the PDD curves acquired in the PRESAGE by a factor of 1.05, following methodology described in Newton et al [5].

2.2. Clinical small-field IMRT and VMAT
In this study, radiochromic plastic dosimeters, PRESAGE®, were used for clinical small-field dose measurements. Six small cylindrical phantoms (6 cm diameter × 7 cm length) were irradiated with 6 MV MLC-delimited square fields: 6 x 6 mm², 8 x 8 mm², 1 x 1 cm², 1.2 x 1.2 cm², 1.6 x 1.6 cm², and 2 x 2 cm². Five large cylindrical phantoms (10 cm diameter x 11 cm length) were used for clinical small-field IMRT and VMAT dose verification. Five IMRT or VMAT plans, with field sizes ranging 1-4 cm, were selected for dose verification. These plans were selected based on their complexity as to if they passed the patient-specific QA process using MapCheck and ArcCheck. For comparative dosimetry radiochromic EBT3 films, positioned in a 30 x 30 x 10 cm³ solid water phantom, were used for PDD, lateral beam profile, and 2-D dose distribution measurements. EBT3 films were positioned at 1.5 cm depth for MLC-delimited small square field measurements, and at 5 cm depth for all IMRT/VMAT dose measurements. A commercial Epson Expression 11000XL flatbed scanner was used for readout of irradiated EBT3 radiochromic films at 300 dpi resolution, 24 hours after the irradiation.

3. Results
3.1. Preclinical small field dosimetry
The EBT3 film reading protocol, for kV dosimetry, was carefully studied by Wang et al. In this study, films were irradiated at 8 different doses between 1-15 Gy. Each of the films was scanned at 6 different times. For doses between 1-5 Gy, at least 5 hours of developing time is necessary, while for doses
between 7-9 Gy, the developing time should be at least 24 hours. Finally, when the dose is 10 Gy or higher, 48 hours of developing time is suggested to achieve stable results. Percent depth dose curves of 3 different field sizes are shown in Fig. 1. Dose at different depths was normalized to the dose at 5 mm depth instead of the surface to calculate the PDD. This was done because the measurements in the buildup region are less stable than at the deeper depths. For film measurements, two thicknesses of solid water phantom, 2 cm and 6 cm were placed underneath to evaluate the difference of backscattering between couch and solid water phantom.

![Figure 1](image1.png)

**Figure 1.** Comparison of PDD curves from Muriplan, Monte Carlo and film measurement with 2 cm, cm thickness of solid water phantom.

Figures 2 and 3 show PDD and beam profile results using EBT3 radiochromic film and PRESAGE for 3 x 3 mm² and 10 x 10 mm² fields. All curves are normalized to 10 mm depth. The measured beam profiles are compared for depths of 10, 20, and 30 mm in Fig. 2(b) and Fig. 3(b). For the 3 x 3 mm² field size, the differences in PDD among PRESAGE, film axial, and film vertical measurements are within ±1% at depths less than 3 cm. At depths between 3 and 5 cm, PRESAGE has a higher depth dose than film vertical by up to 3%, but agrees with film axial measurements within ±1%.

![Figure 2](image2.png)

**Figure 2.** PDD and beam profile measurements for the 3 x 3 mm² field using EBT3 film and PRESAGE. Depth-dose curves were plotted from 5 to 55 mm, and the beam profiles were compared at depths of 10, 20, and 30 mm.
Figure 3. PDD and beam profile measurements for the 10 x 10 mm$^2$ field using EBT3 film and PRESAGE. Depth-dose curves were measured from 5 to 55 mm, while the beam profiles were measured at 10, 20, and 30 mm depth.

Figure 4. Comparison of beam profiles at 2cm depth from Muriplan, Monte Carlo and film measurement.

In Fig. 4, beam profiles of each field size from film, Monte Carlo, and Muriplan were compared. There are no Muriplan results for 0.5 and 1 mm cone size because of the resolution limitation. Error bars provide standard deviations for the Monte Carlo results.

3.2. Clinical small-field dosimetry

In this study, both EBT3 films and PRESAGE are used for dose verification of clinical small-field dosimetry calculated from Eclipse Acura XB. Fig. 5 presents an experimental evaluation of the Acuros dose calculation accuracy on beam profile, PDD, and dose distribution for the 8 x 8 mm$^2$ MLC-delimited field, using EBT3 films and PRESAGE dosimeters. Figure 6 shows a comparison of dose distributions, for a single IMRT field, from EBT3 and PRESAGE. Gamma index pass rate is 99% with 2% DD (dose difference) and 1 mm DTA (distance-to-agreement) gamma criteria. Figure 7 shows dose verification along the central slice (a) and at the plane 0.8 cm from the isocenter (b), for a VMAT stereotactic radiosurgery. Gamma index pass rate is 98% for (a) and 97.1% for (b), with 2%/1mm gamma criteria. Figure 8 shows dose verification along the central slice (a) and at the plane 1.3 cm from the isocenter (b) for a pancreas SBRT using 9-field IMRT. Gamma index pass rate is 89% for (a) and 78.4% for (b), with 2%/1mm gamma criteria.
Figure 5. Dosimetric comparison for beam profile (a), PDD (b), and 2-D dose distribution (c, d).

Figure 6. Comparison of dose distribution between EBT3 film and PRESAGE measurements for a single IMRT field. 99% gamma index pass rate, with 2% and 1 mm gamma criteria.

Figure 7. Dose verification along the central slice (a) and 0.8 cm from the isocenter (b) for a VMAT stereotactic radiosurgery. Gamma index pass rate is 98% for (a) and 97.1% for (b), with 2% and 1 mm gamma criteria.
Figure 8. Dose verification along the central slice (a) and 1.3 cm from the isocenter (b), for a pancreas SBRT using 9-field IMRT. Gamma index pass rate is 89% for (a) and 78.4% for (b), with 2% and 1mm gamma criteria.

4. Discussion

4.1. Preclinical small field dosimetry

Our beam data measurements indicated a maximum difference between the measured and simulated PDD of each field size as 3.3%, 3.2%, 0.6%, 0.3% and 1.8% for field sizes of 0.5 mm, 1 mm, 3 mm, 5 mm, and 10 mm, respectively. The maximum difference of PDD between Muriplan and simulation was 10.3%, 4.3%, 0.6%, 0.5% and 1.4% at 6 cm, respectively, and at at 2 cm depth, the difference is 3.89%, 5.29%, 0.47%, 0.88% and 0.33%. It should be noted that there was a good agreement of the PDD curves between film measurement and Monte Carlo calculation for all field sizes. Good agreement was also observed between film measurement and Muriplan for field sizes larger than 3 mm. However, Muriplan underestimated the dose for field sizes of 0.5 mm and 1 mm. This could result in overdosing deeper structures during animal irradiations. Furthermore, PDD values increased with field size due to increased scattering. This indicates that percent depth dose decreases more dramatically for small field sizes. In the comparison of PDD curves using 2 cm and 6 cm phantom thickness, no significant dosimetric difference (<±3%) was shown for 0.5, 1, 3, 5, and 10 mm FS, which indicates that the dosimetric difference due to backscattering is negligible when irradiating rodents of 2-6 cm with small field sizes.

Our results in Fig.2 and 3 indicate good agreement overall for PDD curves from PRESAGE and films at depths less than 3 cm for both 10 x 10 mm² and 3 x 3 mm² field sizes. Accurate dosimetry within this depth is sufficient for small animal treatments; however larger depths would become more of a consideration for the treatment of larger rodents such as rats. At 5 cm depth, PRESAGE measurements show a 3% higher depth dose than film vertical measurement, but agrees well with film axial measurement, for both field sizes. The slightly higher PDD values from PRESAGE at low dose region may be due to lower signal-to-noise ratio from the reconstructed images. Additionally, film axial measurements are more prone to alignment error, particularly for small fields, but this drawback is offset by the fact that they are less labor-intensive to set up. Compared with film measurements, the PRESAGE dosimeter has a limitation in acquiring data near the surface as its surface is not perfectly flat. Specifically, dosimetry data at the first 2 mm of depth are more susceptible to measurement error due to these surface irregularities. Given this limitation, however, PRESAGE measurements have the marked advantage of providing 3D dosimetry information and provide an evaluation tool that is less labor intensive to set up properly and measure. If detailed depth dose information is required in the region from the surface to 2 mm depth, it would be useful to use film measurements at these depths to supplement PDD information obtained from PRESAGE measurements.

Another discrepancy we observed in this study is related to penumbra. The penumbra values obtained from PRESAGE are larger than those from EBT3 films by about 0.1 mm for 3x3 mm² and 0.5 mm for 10x10 mm² at 2 cm depth. The larger penumbra from PRESAGE measurement is likely due to larger spatial resolution inherent to the OCT scanner and image noise. Here EBT3 film measurement can offer
an advantage as its high image resolution can provide more accurate penumbra measurements in the case of small field sizes. However, PRESAGE measurements are more efficient than film as it provides more information in one 3D dosimeter and a single optical-CT scan. For FWHM measurements, PRESAGE provides comparable results as EBT3 film, with a small discrepancy of 0.01 mm for 3 x 3 mm² and 0.07 mm for 10 x 10 mm² field size at 2 cm depth. We observed in this study that PRESAGE measured beam profiles exhibit larger uncertainties in flatness and symmetry when compared to film measurements. A possible reason for this is the inherent tradeoff between signal-to-noise ratio and resolution when reconstructing PRESAGE images. More image noise is introduced when the scanning resolution is set higher. These two factors must be balanced to determine an optimized reconstruction protocol. Improvements to scanner setup parameters such as increasing the number of projections and acquired data points for each projection. Additionally, changes can be made to the image reconstruction protocol to further mitigate our resolution limitations. These aspects will be explored in future studies focused on PREGAGE evaluation of small fields.

As for beam profiles, there was good agreement between EBT3 film measurement and Monte Carlo calculations. The largest penumbra difference was 0.05 mm when field size was 0.5 mm. However, the field sizes from Muriplan were consistently smaller than film measurement and simulation. These results indicates that calculations performed by the Muriplan treatment planning system underestimate the field size compared with our measurements and simulation results.

4.2. Clinical small field dosimetry

The use of small fields in radiotherapy has increased significantly, especially in SRS/SBRT and larger IMRT fields that are composed of small beamlets. As such, an experimental evaluation of the dose calculation accuracy for small fields is essential. For small field dosimetry EBT3 film has the advantages of being nearly energy independent, close to water, high resolution, and good for 2-D dosimetry. The lateral beam profiles, for 8 x 8 mm² MLC-delimited field size, shows an excellent agreement in the full width of half maximum (FWHM) and penumbra region between EBT3 and PRESAGE, and an overestimated dose in the penumbra from the Acura XB calculation algorithm. This difference in the penumbra region, between measured results and calculation, may be due to inaccurate small-field modelling of the planning system, but also possibly due to geometric uncertainty of MLC positioning. Figure 5 shows good agreement in beam profile, PDD, and dose distribution, for 8 x 8 mm² MLC field size, between EBT3 and PRESAGE. For PDD curve, the maximum difference between PRESAGE and TPS is 3.7% in the build-up region. There is a good agreement in 2-D dose distribution between EBT3 and PRESAGE, shown in Figure 5 (c), with 98.9% gamma index pass rate. The disagreement of 2-D dose distribution between PRESAGE and TPS, shown in Figure 5(d), can partly be attributed to the poor modelling of MLC leakage. 2-D planar isodose distribution comparison using radiochromic film is currently recommended for dose verification of treatment planning calculation algorithm as well as end-to-end advanced treatment techniques, especially for small fields. Figure 6 demonstrates a very good agreement of planar dose distributions between PRESAGE and EBT3 for a single IMRT field, with a 99% gamma index pass rate for 2%/1mm gamma criteria.

For the treatment planning of complex radiotherapy techniques such as the use of small-field dynamic delivery, additional tests may be required to verify the accuracy of dose calculation for the high dose gradients in a small irradiated volume. For instance, should the dose distribution be verified in one plane, in several planes or the total 3D dose distribution? Figure 7 shows the dose distribution comparison between PRESAGE and Eclipse at two different planes for a VMAT stereotactic radiosurgery in the cervical spine. The PTV has an equivalent spherical dimension of 1 cm and a volume of 0.5 cc. Therefore, the pre-treatment VMAT QA cannot be checked with ArcCheck. The main disadvantage of the 2-D detector arrays, for small field dosimetry, is that they do not offer good spatial resolution as the detector spacing is too large (7 mm). For small-field IMRT/VMAT plans radiochromic film provides a good 2-D dosimetric verification as it has probably the highest intrinsic resolution of detectors which are relatively water equivalent and no energy dependence for MV beams, and has been recommended.
for small field dosimetry [26]. In this case, EBT3 film was used for patient specific pre-treatment QA, and the gamma index pass rate was 97.4% with 2% DD (dose difference) and 1 mm DTA (distance to agreement) gamma criteria. PRESAGE measurement resulted in a 98% pass rate at the plane along the isocenter and 97.1% pass rate at the plane 8mm from the isocenter, providing additional information on dose verification. Presented in Figure 8, it is a pancreas SBRT using 9-field IMRT technique. The PTV has an equivalent spherical dimension of 4.6 cm and a volume of 50.4 cc. The IMRT treatment was highly modulated with a lot of small beamlets, and the IMRT QA, performed with a MapCheck, did not pass the gamma index test. Gamma index pass rate was 90.2% when EBT3 was used for IMRT QA in this case, with 2mm/1% criteria. PRESAGE measurement resulted in 89% gamma index pass rate at the plane along the isocenter and 78.4% pass rate at 1.3 cm from the isocenter. The dose verification at different planes provided useful information in this patient specific IMRT QA. The similarity between EBT3 film and PRESAGE based on the gamma index analysis indicates that PRESAGE is a suitable 3-D dosimeter for special IMRT QA when additional information is required for clinical decision, such as the small-field IMRT/VMAT presented here.

5. Conclusion
This study was driven by the increasing need for dosimetric characterization of image-guided small animal irradiators, as well as for accurate and precise dose verification of clinical small fields which are used for precision radiotherapy techniques.

The results in this study provide a comparison between PRESAGE and EBT3 radiochromic film evaluation of dosimetric characteristics of preclinical small fields. The principal advantage of the PRESAGE dosimeter over radiochromic film is that dose information is three dimensional in nature, allowing simultaneous evaluation of dose within the entire volume. This work also provides valuable commissioning and beam data evaluation techniques to future groups that will be using 3D dosimetry as a tool in this regard.

3-D radiochromic plastic dosimeter, PRESAGE, can be used to acquire small-field megavoltage beam dosimetric parameters precisely and accurately. Both EBT3 film and PRESAGE dosimeter can be used for dose verification of small-field IMRT/VMAT in modern radiotherapy techniques. However, our results indicate that PRESAGE is a suitable 3-D dosimeter for special IMRT QA when additional information is required for clinical decision,

6. References
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