1. Fast Cone-Beam Optical CT Scanning of a Radiochromic Solid Dosimeter for Clinical 3-D Dose Verification

By S J Hoogcanspel, Y Xu, and C Wu

Purpose: There is an urgent need for fast 3-D dose verification for advanced radiotherapy techniques such as IMAT. This study is to evaluate the accuracy and clinical relevance utilizing a fast cone-beam optical CT scanner with a radiochromic solid dosimeter, PRESAGE®. Methods: A first-generation laser optical CT scanner, in conjunction with gels and radiochromic solid dosimeters, has been successfully used for 3-D dose verification of complex treatments such as IMRT and radiosurgery. However, a major limitation with this type scanner is the long scanning time (8-hours), which makes same-day dose verification for treatment impossible. In this study three radiochromic dosimeters (PRESAGE®) were irradiated with 12Mev electron beam, 6MV photon beam, and 5-field IMRT, respectively. Dose readout was performed using a Vista™ cone beam optical scanner (Modus Medical Devices Inc.). This scanner utilizes a LED diffuse light panel and a lens based CCD camera to capture a series of 2D optical projections through the region of interest while the object is being rotated 360°. Feldkamp filtered back projection was used to reconstruct the 3D dose map, with a spatial resolution of 1×1×1mm. Each dosimeter was scanned both before and after irradiation in order to eliminate artifacts caused by light scattering and dosimeter non-uniformity. Dose distributions were compared with results from a first-generation laser optical CT scanner and Eclipse planning system. Results: The PDDs measured with PRESAGE® and the beam data from Eclipse agree within 3% and 1mm. Comparison of the IMRT dose distributions between PRESAGE® measurements and Eclipse calculation shows 93% Gamma index passing rate (3%, 3mm criteria). The scanning time for a 3-D dose map is less then 30 minutes. Conclusions: The Vista™ cone-beam optical CT scanner and radiochromic dosimeter, PRESAGE®, has shown the potential for fast 3-D dose verification.

2. A Patient Specific QA Protocol for Verification of 4D Dosimetry

By F Yin, A Thomas, H Yan, I Vergalasova, J Adamovics, Q Wu, and M Oldham

Purpose: Presently, there is no patient specific dosimetric QA for radiation treatment of moving targets. Here we present a patient specific QA protocol for verification of 4D dosimetry delivered to a moving target in SBRT of lung and liver tumors. Methods and Materials: The protocol proceeds as follows. The patient’s breathing pattern is recorded during 4D simulation and imported to a dynamic phantom incorporating a target that moves within an artificial lung or liver respectively. The patient’s treatment plan (e.g. VMAT) is then recalculated on the free-breathing CT of the dynamic phantom. The target is replaced with a 3D dosimeter (Presage), which is then irradiated while moving with the patient’s breathing pattern. The dose in Presage is determined by optical-CT, and compared with the planned dose, to generate a 4D dose verification index. An end-to-end test of the protocol was performed on a target undergoing known motion (amplitude 1.5cm, frequency 5s). Under-dose and interplay effects were studied in 3DCRT, IMRT, and VMAT treatment plans, where the static target volume was covered 100% with a prescribed dose of 10Gy. Results: The whole process from sample preparation to completion of analysis takes about 1.5 hours for a non-interruptive operation in the chain. Measured 3D dose distributions were obtained for moving phantom targets, for all plans, with isotropic resolution of 1mm3. In the control study, where motion was absent, good agreement was observed between planned and measured dose distributions with a 90% 3D gamma pass rate. Clear evidence of interplay and target under-dosing was observed in all motion deliveries under free breathing. The under-dose at the edge of both ends of the dosimeter along the moving direction was in excess of 30%. Conclusion: Comprehensive patient specific QA of 4D dosimetry for SBRT of moving lung and liver targets is feasible with the Presage/Optical-CT system.
3. **Commissioning a Small Animal Irradiator Using 2D and 3D Dosimetry Techniques**
   By J Newton, M Oldham, Y Li, J Adamovics, and S Das
   From Med. Phys. 38, 3734 (2011) - MO-G-BRB-02
   Purpose: To commission and characterize a novel small animal irradiator, the XRad225cx from Precision X-Ray Inc. This system is capable of delivering both square and circular fields ranging in size from 1mm to 40mm. The combination of very small field size and relatively low energy (225kV) represents a substantial challenge in acquiring accurate dosimetry beam data. This work reports on commissioning studies using 2 independent dosimetry systems: EBT2 radiochromic film and PRESAGE /optical-CT 3D dosimetry.
   Methods: Initial measurements were made with 6x8cm pieces of EBT2 radiochromic film. Output factors were determined at 3 depths (0, 0.5 and 2cm) from films irradiated normally resting on the surface or sandwiched in solid water. Percent-depth-dose (PDD) measurements were made from films also sandwiched in solid water and irradiated edge on. Independent 3D dosimetry measurements were obtained using PRESAGE radiochromic dosimeters and imaged with the Duke Large field-of-view Optical-CT Scanner (DLOS). Output factors and PDD's were obtained using a combination of small fields. Results: The relative output factors and PDD's obtained from EBT2 and PRESAGE showed agreement below 1 cm depth. For field sizes >1cm, relative output factors were found to be stable (~1.00) with differences between PRESAGE and EBT2 <6%. At smaller field sizes the output relative to the 20 mm cone decreased substantially, down to ~0.5 for the smallest 1 mm cone. A slightly greater drop was observed in the PRESAGE measurements, which is currently being investigated. Conclusions: Output factors and PDD curves were successfully obtained for all cones using a combination of EBT2 and PRESAGE. Consistency was observed between both independent measurements after correcting for the lack of exact water equivalence of both the solid water and PRESAGE. The 3D dosimetry system has potential advantages in terms of convenience, efficiency and comprehensiveness when commissioning small fields.

4. **Investigation of PRESAGE® Dosimeters for Proton Therapy**
   By R Grant, G Ibbott, X Zhu, M Carroll, J Adamovics, M Oldham, and D Followill
   Purpose: To evaluate a formulation of PRESAGE® intended for proton therapy and to use it to compare measurements with calculations for a spot scanning pencil proton beam and a passively scattered proton beam. Methods: Two 7.5 cm high by 9.5 cm diameter cylindrical PRESAGE® dosimeters were used. CT images were used to design two treatment plans with an Eclipse treatment planning system (TPS). The first plan used a single pencil beam of energy 153.2 MeV to provide a range of 16 cm in water. Four regions of the dosimeter were irradiated delivering doses in the peak of approximately 6, 10, 13 and 19 Gy(RBE) by rotating the dosimeter between spot deliveries. The second plan used a single passively scattered field with a spread out Bragg peak (SOBP) of 4 cm. This plan delivered approximately 10 Gy(RBE). The dosimeters were analyzed using an optical CT scanner. The measured optical densities were converted to dose via a calibration curve, exported to the CERR environment and fused to the treatment plan. Dose distributions were scaled to the SOBP plan. Dose profiles were taken along the axis of each spot and the SOBP and perpendicularly across the SOBP. Results: The dose measured in the peak of single spot irradiations increased proportionally to the MU setting. The distal falloff was steeper than predicted by the TPS. The cross profiles for the SOBP plan matched within 2 mm with the TPS. The depth profile was noisy within the modulated area. Noise decreased as dose increased for both dosimeters. Conclusions: This formulation of PRESAGE® shows promise as a 3D dosimeter for proton therapy. A dose calibration specific to protons will facilitate further analysis and enable measurement of complex distributions.
5. **3D Dosimetry for Small Irregular Proton Fields Using a New PRESAGE® Dosimeter**
   By L Zhao, J Newton, J Adamovics, M Oldham, C Cheng, and I Das
   Purpose: Small field dosimetry is challenging that impacts patient specific QA in proton beam therapy due to detector size, aperture scattering and disequilibrium. Therefore, it is urgent to develop an accurate and efficient method to quantify the uncertainty of 3D dosimetry of small fields. This study investigated the feasibility of using a new formula PRESAGE® for 3D dosimetry of small irregular field in proton therapy.
   Methods: Three cylindrical shape PRESAGE® dosimeters (10 cm or 4 cm in diameter, 6 cm in length) of a new formula \( \text{C}_{304}\text{H}_{510}\text{N}_{20}\text{O}_{71}\text{SBr} \) were irradiated with three irregular patient fields (field size 2–4 cm) either with or without range compensators, respectively. A proton range 6 cm with three different SOBP widths were used. To test the sensitivity of the dosimeter, three different dose levels, 150, 300, and 500 cGy were delivered. Uniform scanning proton beams with energy stacking were used for beam delivery. Three corresponding treatment plans created on the CMS XiO treatment planning system using pencil beam algorithm were compared with the experimental results in the form of relative dose distributions, including isodose plots, dose profiles and gamma index maps.
   Results: Transverse dose profile comparison showed spatial agreement within 1–2 mm. The measured depth dose results showed a sharper distal fall off compared to the calculations with negligible quenching effect (< 5%). Most differences were observed in the high dose gradient region (field edges and distal end). Majority of the data points in the target region passed the 3% dose difference and 3 mm DTA gamma analysis.
   Conclusions: Good agreement was observed between planned and measured 3D dose distributions. Overall, the new formula PRESAGE® dosimeter was found to be suitable for verifying the 3D dose distribution for small irregular fields in proton therapy with single shot irradiation.

6. **Sophisticated test objects for the quality assurance of optical computed tomography scanners**
   By A T Abdul Rahman, Elke Br"auer-Krisch, Thierry Brochard, John Adamovics, S K Clowes, David Bradley and Simon J Doran,
   Five 60 mm diameter cylindrical PRESAGE® samples were irradiated using the x-ray microbeam radiation therapy facility on the ID-17 biomedical beamline at the European Synchrotron Radiation Facility. Samples were then imaged on the University of Surrey parallel-beam optical CT scanner.

7. **Investigation of radiological properties and water equivalency of PRESAGE dosimeters**
   By Gorjiara, Tina; Hill, Robin; Kuncic, Zdenka; Adamovics, John; Bosi, Stephen; Kim, Jung-Ha; Baldock, Clive
   Purpose: PRESAGE is a dosimeter made of polyurethane, which is suitable for 3D dosimetry in modern radiation treatment techniques. Since an ideal dosimeter is radiol. water equiv., the authors investigated water equivalency and the radiol. properties of three different PRESAGE formulations that differ primarily in their elemental comps. Two of the formulations are new and have lower halogen content than the original formulation.
   Methods: The radiol. water equivalence was assessed by comparing the densities, interaction probabilities, and radiation dosimetry properties.

8. **Locating Radiation Hazards and Sources within Contaminated Areas by Implementing a Reverse Ray Tracing Technique in the RadBall Technology**
   By Eduardo B. Farfán, Steven Stanley, Christopher Holmes, Kathryn Lennox, Mark Oldham, Corey Clift and John Adamovics
   From Health Physics Journal March 3, 2011
   RadBall is a novel technology that can locate and quantify unknown radioactive hazards within contaminated areas, hot cells, and glove boxes. The device consists of a colander-like
outer tungsten collimator that houses a radiation-sensitive polymer semi-sphere. The collimator has a number of small holes; as a result, specific areas of the polymer are exposed to radiation becoming increasingly more opaque in proportion to the absorbed dose. The polymer semi-sphere is imaged in an optical computed tomography scanner that produces a high resolution 3D map of optical attenuation coefficients. A subsequent analysis of the optical attenuation data using a reverse ray tracing technique provides information on the spatial distribution of gamma ray sources in a given area forming a 3D characterization of the area of interest. The RadBall technology and its reverse ray tracing technique were investigated using known radiation sources at the Savannah River Site’s Health Physics Instrument Calibration Laboratory and unknown sources at the Savannah River National Laboratory’s Shielded Cells.

9. **Dosimetry tools and techniques for IMRT**  
By Daniel A. Low, Jean M. Moran, James F. Dempsey, Lei Dong, and Mark Oldham  
From Med. Phys. 38, 1313 (2011)  
AAPM Task Group 120 update.

10. **Temperature dependence of the dose response for a solid-state radiochromic dosimeter during irradiation and storage**  
By Peter S. Skyt, Jørgen B. B. Petersen, Esben S. Yates and Ludvig P. Muren  
Due to the exponential dependencies, stabilization of the dosimeter during irradiation at low temperatures (e.g., 5°C) is preferable in clinical use to optimize the accuracy of the dose response. In addition, a low storage temperature is recommended in order to minimize the post-irradiation temporal change in dose response and thereby increase the post-irradiation stability of the dosimeter. The measurements in this study show that if the observed temperature and temporal dependencies are not considered, this could potentially deteriorate the accuracy of the dosimeter.

11. **An investigation into a new re-useable 3D radiochromic dosimetry material, PresageREU**  
By Pierquet, Michael; Thomas, Andrew; Adamovics, John; Oldham, Mark  
From Journal of Physics: Conference Series (2010), 250  
Purpose: To investigate the dosimetric properties of a new Presage formulation which exhibits a reversible color change on exposure to radiation. PresageREU offers the intriguing possibility of the first re-useable 3D dosimetry material. Method and Materials: Small vols. of PresageREU in 1 × 1 × 5 cm optical cuvettes were irradiated and re-irradiated under a variety of conditions and times to investigate a range of properties including re-usability, dose-rate dependence, dose sensitivity, temporal response, energy sensitivity, and temp. dependence.

12. **3-D Dosimetric Comparison of IMRT with 2.5 Mm HD120 MLC Using Optical CT Based Polymer Gel and PRESAGE Dosimeters**  
By C Wuu, Y Xu, M Maryanski, and J Adamovics  
Purpose: To evaluate and compare the 3-D dose distributions for IMRT with 2.5 mm HD120 MLC using optical CT based polymer gel and PRESAGE dosimeters. Method and Materials: In this study, a polymer BANG gel dosimeter and a PRESAGE phantom, together with an optical CT scanner, were employed to implement 3-D dose distribution measurements. Both dosimeters, with 15 cm diameter and 14 cm height, were modified to optimal and linear dose-response characteristics. A slice thickness of 2.5 mm without spacing was used for CT simulation on both the patient and cylindrical phantoms. The Varian Eclipse
treatment planning system was used to design the IMRT radiosurgery plan for a patient with a 2.5 cc small brain tumor treated with 6 MV photon beams. To correlate the optical density response with radiation dose, the same batch of gel and PRESAGE phantoms were irradiated with a 16 MeV electron beam to a known dose at the depth of dmax. The optical density at a specific depth and the PDD table of the electron beam can be used to obtain the optical density dose response of the dosimeters. Both phantoms were scanned with 1 mm pixel resolution using a commercial optical CT scanner, OCTOPUS™ (MGS Research Inc., Madison, CT). Results: Both measured dose distributions from gel and PRESAGE and calculated results are in reasonable agreement. However, the isodose lines from the measurements show more variation than those from the calculation, and this trend is more significant for the 2.5 mm MLC. These discrepancies may be partly attributed to the fact that the calculation grid for the planning system is 2.5 mm yet the resolution of gel measurements is 1 mm, as well as the Trilogy TX having a smaller leaf width. Issues and difficulties on 3-D dosimetric comparison will be presented.

13. An investigation of the potential of optical computed tomography for imaging of synchrotron-generated x-rays at high spatial resolution
By Doran Simon J; Brochard Thierry; Adamovics John; Krstajic Nikola; Brauer-Krisch Elke
From Physics in medicine and biology (2010), 55(5), 1531-47.
X-ray microbeam radiation therapy (MRT) is a novel form of treatment, currently in its preclinical stage, which uses microplanar x-ray beams from a synchrotron radiation source. It is important to perform accurate dosimetry on these microbeams, but, to date, there has been no accurate enough method available for making 3D dose measurements with isotropic, high spatial resolution to verify the results of Monte Carlo dose simulations. Here, we investigate the potential of optical computed tomography for satisfying these requirements.

14. An investigation of the response of the radiochromic dosimeter PRESAGE to irradiation by 62 MeV protons
By Al Nowais, Shamsa; Kacperek, Andrzej; Brunt, John N. H.; Adamovics, John; Nisbet, Andrew; Doran, Simon J.
From Journal of Physics: Conference Series (2010), 250
Measurements of the 62 MeV proton beam at the Clatterbridge Center for Oncol. using the radiosensitive plastic PRESAGE have previously shown a dependence of the dosimeter sensitivity (dose-response slope) on the linear energy transfer (LET) of the ionising particles. This work focuses on a possible explanation in terms of track structure theory (TST). Exptl. measurements of highly irradiated PRESAGE samples established the D37 parameter of the theory to be of the order of 1000 Gy. Initial attempts at applying the theory showed good agreement of the theor. and exptl. values .

15. Creation of sophisticated test objects for quality assurance of optical computed tomography scanners
By Abdul Rahman, A. T.; Brauer-Krisch, Elke; Brochard, Thierry; Adamovics, John; Clowes, Steve; Bradley, David; Doran, Simon
From Journal of Physics: Conference Series (2010), 250
Optical computed tomog. (CT) shows great potential for radiation therapy dose verification in 3D. However, an effective quality assurance regime for the various scanners currently available still remains to be developed. We show how the favorable properties of the PRESAGE radiochromic polymer may be exploited to create highly sophisticated QA phantoms. Five 60 mm-diam. cylindrical PRESAGE samples were irradiated using the x-ray microbeam radiation . therapy facility on the ID17 biomedical beamline at the European Synchrotron Radiation Facility. Samples were then imaged on the University of Surrey.
16. **Determination of the depth dose distribution of proton beam using PRESAGE dosimeter**
   By Zhao, L.; Das, I. J.; Zhao, Q.; Thomas, A.; Adamovics, J.; Oldman, M.
   From Journal of Physics: Conference Series (2010), 250
   PRESAGe dosimeter dosimeter has been proved useful for 3D dosimetry in conventional photon therapy and IMRT. Our objective is to examine the use of PRESAGE dosimeter for verification of depth dose distribution in proton beam therapy. Three PRESAGE samples were irradiated with a 79 MeV unmodulated proton beam. Percent depth dose profile measured from the PRESAGE dosimeter is compared with data obtained in a water phantom using a parallel plate Advanced Markus chamber. The Bragg-peak position detd. from the PRESAGE is within 2 mm compared to measurements in water.

17. **Electron dosimetry in the presence of small cavities**
   By Doran, Simon; Thomas, Russell; Hollingdale, Rachel; Adamovics, John; Nisbet, Andrew
   From Journal of Physics: Conference Series (2010), 250
   Tissue inhomogeneities such as bones or air cavities give rise to significant perturbations of dose during electron radiotherapy. While these can be calc. using a variety of computational methods, accurate exptl. verification has hitherto been difficult. In this study, we used 3-D optical computed tomog. (CT) dosimetry of PRESAGE samples to obtain central-axis depth dose curves and to study the dose distribution around a simple air cavity. Some concerning anomalous results were obtained for the build-up region of the depth-dose curve, which are currently under investigation.

18. **Light scattering in optical CT scanning of Presage dosimeters**
   By Xu, Y.; Adamovics, J.; Cheeseborough, J. C.; Chao, K. S.; Wuu, C. S.
   From Journal of Physics: Conference Series (2010), 250
   The intensity of the scattered light from the Presage dosimeters was measured using a Thorlabs PM100D optical power meter with an optical sensor of 1 mm diam. sensitive area. Five Presage dosimeters were made as cylinders of 15.2 cm, 10 cm, 4 cm diams. and irradiated with 6 MV photons using a Varian Clinac 2100EX. Each dosimeter was put into the scanning tank of an OCTOPUS optical CT scanner filled with a refractive index matching liq. A laser diode was positioned at one side of the water tank to generate a stationary laser beam of 0.8 mm width.

19. **RadBall technology testing and MCNP modeling of the tungsten collimator**
   By Farfan, Eduardo B.; Foley, Trevor Q.; Coleman, J. Rusty; Jannik, G. Timothy; Holmes, Christopher J.; Oldham, Mark; Adamovics, John; Stanley, Steven J.
   From Journal of Physics: Conference Series (2010), 250
   The United Kingdom's National Nuclear Lab. (NNL) has developed a remote, non-elec., radiation-mapping device known as RadBall, which can locate and quantify radioactive hazards within contaminated areas of the nuclear industry. RadBall consists of a colander-like outer shell that houses a radiation-sensitive polymer sphere. The outer shell works to collimate radiation sources and those areas of the polymer sphere that are exposed react, becoming increasingly more opaque, in proportion to the absorbed dose. The polymer sphere is imaged in an optical-CT scanner.

20. **RadBall Technology Testing in the Savannah River Site's Health Physics Instrument Calibration Laboratory**
   By Farfan, Eduardo B.; Foley, Trevor Q.; Jannik, G. Timothy; Harpring, Larry J.; Gordon, John R.; Blessing, Ronald; Coleman, J. Rusty; Holmes, Christopher J.; Oldham, Mark; Adamovics, John; et al
   The United Kingdom's National Nuclear Lab. (NNL) has developed a radiation-mapping device that can locate and quantify radioactive hazards within contaminated areas of the nuclear industry. The device, known as RadBall, consists of a colander-like outer collimator that houses a radiation-sensitive polymer sphere. The collimator has over two hundred small holes; thus, specific areas of the polymer sphere are
exposed to radiation becoming increasingly more opaque in proportion to the absorbed dose. The polymer sphere is imaged in an optical-CT scanner that produces a high resoln. 3D map.

21. Study of dosimetric water equivalency of PRESAGE for megavoltage and kilovoltage x-ray beams
By Gorjia, Tina; Hill, Robin; Kim, Jung-Ha; Kuncic, Zdenka; Adamovics, John; Baldock, Clive
From Journal of Physics: Conference Series (2010), 250
PRESAGE is a dosimeter that is suitable for 3D dosimetry. To be used as an ideal dosimeter, however, it should present radiol. water equiv. properties. In this work, we have investigated the radiol. properties of three different PRESAGE formulations. The radiol. water equivalence was assessed by comparing the photon cross sections and radiation dosimetry properties of the three different PRESAGE formulations with the corresponding values for water. Relative depth doses were calcld. using Monte Carlo methods for 75, 125, 180 and 280 kVp and 6 MV x-ray beams.

22. Three-dimensional dosimetry of a beta-emitting radionuclide using PRESAGE dosimeters
By Grant, R. L.; Crowder, M. L.; Ibott, G. S.; Simon, J.; Frank, R. K.; Rogers, J.; Loy, H. M.; Adamovics, J.; Newton, J.; Oldham, M.; et al
From Journal of Physics: Conference Series (2010), 250
Three-dimensional dose distributions from liq. brachytherapy were measured using PRESAGE dosimeters. The dosimeters were exposed to Y-90 for 5.75 days and read by optical tomog. The distributions are consistent with ests. from beta dose kernels.

23. A ‘quad-phantom’ film dosimeter for use as a multi-planar verification tool for PRESAGE/optical-CT
By L Stunja, A Thomas, J Adamovics, J Deasy, M Oldham
From Journal of Physics: Conference Series (2010), 250
To develop and characterize the accuracy and reproducibility of a „quad-phantom” dosimeter which will serve as an independent verification tool during commissioning of a PRESAGE/optical-CT 3D dosimetry system. A 16cm x 12cm cylindrical quad-phantom was constructed from four pieces of solid polyurethane mimicking the PRESAGE material. Films were placed and anchored in orthogonal planes and the quad-phantom was fastened tightly together and placed in a water-filled Styrofoam container for irradiation. A simple, two-field plan consisting of 6x6cm anterior-posterior and right-lateral 6MV photon beams (400cGy) was delivered three times (fresh films inserted for each) with a Varian Clinac 600C.

24. Toward acquiring comprehensive radiosurgery field commissioning data using the PRESAGE/optical-CT 3D dosimetry system
By Clift Corey; Thomas Andrew; Adamovics John; Chang Zheng; Das Indra; Oldham Mark
From Physics in medicine and biology (2010), 55(5), 1279-93.
Achieving accurate small field dosimetry is challenging. This study investigates the utility of a radiochromic plastic PRESAGE read with optical-CT for the acquisition of radiosurgery field commissioning data from a Novalis Tx system with a high-definition multileaf collimator (HDMLC). Total scatter factors (Sc, p), beam profiles, and penumbrae were measured for five different radiosurgery fields (5, 10, 20, 30 and 40 mm) using a commercially available optical-CT scanner (OCTOPUS, MGS Research). The percent depth dose (PDD), beam profile and penumbra of the 10 mm field were also measured.
25. **Investigation into the feasibility of using PRESAGETM/optical-CT dosimetry for the verification of gating treatments**

By Samuel L Brady, William E Brown, Corey G Clift, Sua Yoo and Mark Oldham


This work presents an investigation into the use of PRESAGE dosimeters with an optical-CT scanner as a 3D dosimetry system for quantitative verification of respiratory-gated treatments. The CIRS dynamic thorax phantom was modified to incorporate a moving PRESAGE dosimeter simulating respiration motion in the lungs. A simple AP/PA lung treatment plan was delivered three times to the phantom containing a different but geometrically identical PRESAGE insert each time. Each delivery represented a treatment scenario: static, motion (free-breathing) and gated. The dose distributions, in the three dosimeters, were digitized by the optical-CT scanner. Improved optical-CT readout yielded an increased signal-to-noise ratio by a factor of 3 and decreased reconstruction artifacts compared with prior work. Independent measurements of dose distributions were obtained in the central plane using EBT film. Dose distributions were normalized to a point corresponding to the 100% isodose region prior to the measurement of dose profiles and gamma maps. These measurements were used to quantify the agreement between measured and ECLIPSE dose distributions. Average gamma pass rates between PRESAGE and EBT were >99% (criteria 3% dose difference and 1.2 mm distance-to-agreement) for all three treatments. Gamma pass rates between PRESAGE and ECLIPSE 3D dose distributions showed excellent agreement for the gated treatment (100% pass rate), but poor for the motion scenario (85% pass rate). This work demonstrates the feasibility of using PRESAGE/optical-CT 3D dosimetry to verify gating-enabled radiation treatments. The capability of the Varian gating system to compensate for motion in this treatment scenario was demonstrated.

26. **A comprehensive evaluation of the PRESAGE/optical-CT 3D dosimetry system**

By Sakhalkar H S; Adamovics J; Ibbott G; Oldham M

From Medical physics (2009), 36(1), 71-82.

This work presents extensive investigations to evaluate the robustness (intradosimeter consistency and temporal stability of response), reproducibility, precision, and accuracy of a relatively new 3D dosimetry system comprising a leuco-dye doped plastic 3D dosimeter (PRESAGE) and a commercial optical-CT scanner (OCTOPUS 5x scanner from MGS Research, Inc). Four identical PRESAGE 3D dosimeters were created such that they were compatible with the Radiologic Physics Center (RPC) head-and-neck (H&N) IMRT credentialing phantom. Each dosimeter was irradiated with a rotationally symmetric arrangement.

27. **A preliminary analysis of LET effects in the dosimetry of proton beams using PRESAGE and optical CT**

By Al-Nowais, S.; Doran, S.; Kacperek, A.; Krstajic, N.; Adamovics, J.; Bradley, D.


PRESAGE is a solid dosimeter based on a clear polyurethane matrix doped with radiochromic components (leuco dyes). On exposure to ionizing radiation a color change is generated in the dosimeter, and hence an optical absorption or optical density change that can be read out by optical CT. The main focus of present investigations has been to investigate the possible LET dependence of PRESAGE to the dose deposited at the Bragg maxima using proton beam absorbed dose measurements, and the linearity of response of the dosimeter. Proton irradiations were performed using the UK proton beam facility.
28. An investigation into the robustness of Optical-CT dosimetry of a radiochromic dosimeter compatible with the RPC Head-and-Neck Phantom

By Sakhalkar, H. S.; Adamovics, J.; Ibbott, G.; Oldham, M.
From Journal of Physics: Conference Series (2009), 164
The potential of the PRESAGE/Optical-CT system as a comprehensive 3D dosimetry tool has been demonstrated. The current study focused on detailed characterization of robustness (intra-dosimeter uniformity and temporal stability) and reproducibility (inter-dosimeter reproducibility) of PRESAGE inserts compatible with the RPC H&N phantom. In addition, the accuracy and precision of PRESAGE dose measurement was also evaluated. Four identical PRESAGE dosimeters (10cm diam. and 7cm height cylinders) were irradiated with the same rotationally symmetric treatment plan using a Varian accelerator.

29. Dosimetry of the microSelectron-HDR Ir-192 source using PRESAGE and optical CT

By Wai P; Adamovics J; Krstajic N; Ismail A; Nisbet A; Doran S
From Applied radiation and isotopes : including data, instrumentation and methods for use in agriculture, industry and medicine (2009), 67(3), 419-22
Optical CT, using a solid polyurethane (PRESAGE) radiochromic dosimeter, has been used to evaluate dose distributions produced by the microSelectron-HDR Ir-192 source. The anisotropy functions obtained through optical CT are in good agreement with Monte Carlo and previously published results especially at polar angle above 20 degrees. The results indicated an evident potential for using solid polymer dosimetry as an accurate method for 3-D dosimetry, although refinements to the existing methods are necessary before the technique can be used clinically.

30. Investigating the feasibility of 3D dosimetry in the RPC IMRT H&N phantom

By Sakhalkar, H. S.; Sterling, D.; Adamovics, J.; Ibbott, G.; Oldham, M.
From Journal of Physics: Conference Series (2009), 164
An urgent requirement for 3D dosimetry has been recognized because of high failure rate (~25%) in RPC credentialing, which relies on point and 2D dose measurements. Comprehensive 3D dosimetry is likely to resolve more errors and improve IMRT quality assurance. This work presents an investigation of the feasibility of PRESAGE/optical-CT 3D dosimetry in the Radiol. Physics Center (RPC) IMRT H&N phantom. The RPC H&N phantom (with std. and PRESAGE dosimetry inserts alternately) was irradiated with the same IMRT plan. The TLD and EBT film measurement data from std. insert irradiation was provided.

31. Investigation of the feasibility of relative 3D dosimetry in the Radiologic Physics Center Head and Neck IMRT phantom using presage/optical-CT

By Sakhalkar Harshad; Sterling David; Adamovics John; Ibbott Geoffrey; Oldham Mark
From Medical physics (2009), 36(7), 3371-7
This study presents the application of the Presage/optical-CT 3D dosimetry system for relative dosimetry in the Radiologic Physics Center (RPC) Head and Neck (H&N) IMRT phantom. Performance of the system was evaluated by comparison with the "gold-standard" RPC credentialing test. A modified Presage cylindrical insert was created that extended the capability of the RPC H&N phantom to 3D dosimetry. The RPC phantom was taken through the entire treatment planning procedure with both the standard RPC insert and the modified Presage insert. An IMRT plan was created to match the desired dose construct.

32. RADBALL: a new departure for 3-D dosimetry

By Doran, Simon J.; Stanley, Steven J.; Jenneson, Paul M.; Prott, Erwan; Adamovics, John
From Journal of Physics: Conference Series (2009), 164
This paper describes a new device, RADBALL for mapping environmental radiation fields, as found in the area of nuclear decontamination. The system consists of a specially shaped PRESAGE dosimeter, which
sits inside a custom-designed lead collimator. This is imaged using optical CT to yield data from which the position of either point sources or extended objects may be reconstructed. The principle of the technique is explained, simulations and preliminary data are given and the current design of the dosimeter and collimator are presented.

33. An investigation of the accuracy of an IMRT dose distribution using two- and three-dimensional dosimetry techniques

By Oldham Mark; Sakhalkar Harshad; Guo Pengyi; Adamovics John
From Medical physics (2008), 35(5), 2072-80.

Complex dose delivery techniques like intensity-modulated radiation therapy (IMRT) require dose measurement in three dimensions for comprehensive validation. Previously, we demonstrated the feasibility of the “PRESAGE™/optical-computed tomography (CT)” system for the three-dimensional verification of simple open beam dose distributions where the planning system was known to be accurate. The present work extends this effort and presents the first application of the PRESAGE™/optical-CT system for the verification of a complex IMRT distribution. A highly modulated 11 field IMRT plan was delivered to a cylindrical PRESAGE™ dosimeter (16 cm in diameter and 11 cm in height), and the dose distribution was readout using a commercial scanning-laser optical-CT scanner. Comparisons were made with independent GAFCHROMIC® EBT film measurements, and the calculated dose distribution from a commissioned treatment planning system (ECLIPSE®). Isodose plots, dose profiles, gamma maps, and dose-volume histograms were used to evaluate the agreement. The isodose plots and dose profiles from the PRESAGE™/optical-CT system were in excellent agreement with both the EBT measurements and the ECLIPSE® calculation at all points except within 3 mm of the outer edge of the dosimeter where an edge artifact occurred. Excluding this 3 mm rim, gamma map comparisons show that all three distributions mutually agreed to within a 3% (dose difference) and 3 mm (distance-to-agreement) criteria. A 96% gamma pass ratio was obtained between the PRESAGE™ and ECLIPSE® distributions over the entire volume excluding this rim. In conclusion, for the complex IMRT plan studied, and in the absence of inhomogeneities, the ECLIPSE® dose calculation was found to agree with both independent measurements, to within 3%, 3 mm gamma criteria.

34. Fast, high-resolution 3D dosimetry utilizing a novel optical-CT scanner incorporating tertiary telecentric collimation

By Sakhalkar H S and Oldham M

This study introduces a charge coupled device (CCD) area detector based optical-computed tomography (optical-CT) scanner for comprehensive verification of radiation dose distributions recorded in non-scattering radiochromic dosimeters. Defining characteristics include: (i) a very fast scanning time of ∼5 min to acquire a complete three-dimensional (3D) dataset, (ii) improved image formation through the use of custom telecentric optics, which ensures accurate projection images and minimizes artifacts from scattered and stray-light sources, and (iii) high resolution (potentially 50 μm) isotropic 3D dose readout. The performance of the CCD scanner for 3D dose readout was evaluated by comparison with independent 3D readout from the single laser beam OCTOPUS™-scanner for the same PRESAGE™ dosimeters. The OCTOPUS™ scanner was considered the “gold standard” technique in light of prior studies demonstrating its accuracy. Additional comparisons were made against calculated dose distributions from the ECLIPSE treatment-planning system. Dose readout for the following treatments were investigated: (i) a single rectangular beam irradiation to investigate small field and very steep dose gradient dosimetry away from edge effects, (ii) a 2-field open beam parallel-opposed irradiation to investigate dosimetry along steep dose gradients, and (iii) a 7-field intensity modulated radiation therapy (IMRT) irradiation to investigate dosimetry for complex treatment delivery involving modulation of fluence and for dosimetry along moderate dose gradients. Dose profiles, dose-difference plots, and gamma maps were employed to evaluate.
quantitative estimates of agreement between independently measured and calculated dose distributions. Results indicated that dose readout from the CCD scanner was in agreement with independent gold-standard readout from the OCTOPUS™-scanner as well as the calculated ECLIPSE dose distribution for all treatments, except in regions within a few millimeters of the edge of the dosimeter, where edge artifact is predominant. Agreement of line profiles was observed, even along steep dose gradients. Dose difference plots indicated that the CCD scanner dose readout differed from the OCTOPUS™ scanner readout and ECLIPSE calculations by ∼10% along steep dose gradients and by ∼5% along moderate dose gradients. Gamma maps (3% dose-difference and 3 mm distance-to-agreement acceptance criteria) revealed agreement, except for regions within 5 mm of the edge of the dosimeter where the edge artifact occurs. In summary, the data demonstrate feasibility of using the fast, high-resolution CCD scanner for comprehensive 3D dosimetry in all applications, except where dose readout is required close to the edges of the dosimeter. Further work is ongoing to reduce this artifact.

35. Radiological properties of the PRESAGE and PAGAT polymer dosimeters
By Brown S; Venning A; De Deene Y; Vial P; Oliver L; Adamovics J; Baldock C

The radiological properties of the PRESAGE and PAGAT polymer dosimeters have been investigated and their water equivalence determined for use in radiotherapy dosimetry. The radiological water equivalence of each of the polymer dosimeters was determined by comparing the photon and electron interaction cross-sections over the 10 keV-20 MeV energy range and by Monte Carlo modelling the depth dose from a linear accelerator using the BEAMnrc software package. PRESAGE was found to have an effective Z-value and mass density (kgm(-3)) approximately 17% and 10% higher than water, respectively. A maximum difference of 85% was discovered in the photoelectric interaction probability curve of PRESAGE when compared to water over the energy range 10-100 keV, partially due to the Z(3) dependence of the photoelectric effect. The mass radiative stopping power ratios and mass scattering power ratios were both found to have less than 9% difference from water. The depth dose for PRESAGE from a 6MV photon beam had an absolute percentage difference to water of less than 2% and a relative percentage difference of less than 8%. The mass density of PAGAT was found to be 2.6% higher than water due to its high gelatine and monomer concentration. The cross-sectional attenuation and absorption coefficient ratios were found to be within 5% for energies between 10 and 100 keV and within 1% for energies between 100 keV and 20 MeV. The mass collisional stopping power, mass radiative stopping power and mass scattering power ratios were all less than 1% over the energy range studied. The depth dose had an absolute percentage difference to water of less than 1% and a relative percentage difference of less than 2.5%. These results indicate that the PAGAT polymer gel formulation is more radiological water equivalent than the PRESAGE formulation. However, the PRESAGE dosimeter offers some advantages in terms of ease of use and its lack of water equivalence may be overcome with dosimetric correction factors.

36. Three-dimensional shaped solid dosimeter and method of use
By Adamovics, John A.

The invention relates to a solid plastic three-dimensional dosimeter which is useful in treatment planning, optimization of the radiation field, dose verification, dose validation, commissioning, and quality assurance of complex radiotherapy procedures. Dosimeters of the invention can be formed in any clin. relevant shape, and contain a reporter leuco dye which forms a colored image upon irradiation.
37. **A practical three-dimensional dosimetry system for radiation therapy**
   By Guo Pengyi; Adamovics John; Oldham Mark
   From Medical physics (2006), 33(10), 3962-72.
   There is a pressing need for a practical three-dimensional (3D) dosimetry system, convenient for clinical use, and with the accuracy and resolution to enable comprehensive verification of the complex dose distributions typical of modern radiation therapy. Here we introduce a dosimetry system that can achieve this challenge, consisting of a radiochromic dosimeter (PRESAGE) and a commercial optical computed tomography (CT) scanning system (OCTOPUS). PRESAGE is a transparent material with compelling properties for dosimetry, including insensitivity of the dose response to atmospheric exposure.

38. **Characterisation of PRESAGE: a new 3-D radiochromic solid polymer dosimeter for ionising radiation**
   By Adamovics, J.; Maryanski, M. J.
   For the past 50 years there has been interest in developing 3-D dosemeters for ionizing radiation. Particular emphasis has been put on those dosimeters that change their optical properties in proportion to the absorbed dose. Many of the dosimeters that have been evaluated have had limitations such as lack of transparency, diffusion of the image of the dose distribution or poor stability of baseline optical density. Many of these performance limitations have been overcome by the development of PRESAGETM, an optically clear polyurethane-based radiochromic 3-D dosemeter. The solid PRESAGETM dosemeter is formulated with a free radical initiator and a leuco dye and it does not require a container to maintain its shape. The polyurethane matrix is tissue equivalent and prevents the diffusion of the dose distribution image. There is a linear dose–response, which is independent of both photon energy and dose rate. Simple precautions such as preventing long-term exposure to additional ionizing radiation including ultraviolet and controlling storage temperatures prevent the bleaching of the radiochromic response field within the irradiated dosimeter.

39. **Characterization of a new radiochromic three-dimensional dosimeter**
   By Guo P Y; Adamovics J A; Oldham M
   From Medical physics (2006), 33(5), 1338-45. Language: English,
   The development of intensity-modulated radiotherapy (IMRT) has created a clear need for a dosimeter that can accurately and conveniently measure dose distributions in three dimensions to assure treatment quality. PRESAGE is a new three dimensional (3D) dosimetry material consisting of an optically clear polyurethane matrix, containing a leuco dye that exhibits a radiochromic response when exposed to ionizing radiation. A number of potential advantages accrue over other gel dosimeters, including insensitivity to oxygen, radiation induced light absorption contrast rather than scattering response.

40. **Investigation of the dosimetric characteristics of PRESAGE**
   By Guo, Pengyi; Adamovics, John; Oldham, Mark
   PRESAGE is a new material that was recently introduced with some potentially advantageous properties for 3-dimensional dosimetry. The fundamental dosimetric characteristics of PRESAGE were studied to determine its potential for dosimetry. A new method designed to enable rapid, accurate and convenient evaluation of any material which has an optical dose-response, and can be formed into columns of precise dimension (e.g. spectro-photometric cuvettes), was developed. PRESAGE represents a significant step forward in the development towards a truly practical and convenient 3-dimensional dosimetry.
41. **Measurement of a 200 MeV proton beam using a polyurethane dosimeter**  
   By Heard, Malcolm; Adamovics, John; Ibbott, Geoffrey  
   PRESAGE is a 3-dimensional polyurethane dosimeter contg. a leuco dye that generates a color change when irradiated and responds monotonically to both photons and electrons. The response of PRESAGE to p beam radiotherapy was studied. The under-response of polymer gels in the distal region of the spread-out Bragg peak (SOBP) was obsd. in a previous study. The under-response of the PRESAGE is expected because free radicals can recombine in the high LET region resulting in fewer radicals for initiation of the response in the dosimeter. This applies particularly to the distal edge of the SOBP.

42. **PRESAGE - Development and optimization studies of a 3D radiochromic plastic dosimeter - Part 1**  
   By Adamovics, J.; Jordan, K.; Dietrich, J.  
   The polymn. of 6 different transparent plastics as potential 3-dimensional dosimeter matrixes was studied.  
   6 Different leuco dyes and 16 different free radical initiators were evaluated and the photoreactivity of the dosimeter was studied so that the effect of exposure to UV could be minimized. A polyurethane matrix with 2% LMG leuco dye contg. a C halogen initiator is sensitive to high energy radiation and has a linear response to dose. However, this potential 3-dimensional dosimeter must be protected from UV and blue light.

43. **PRESAGE - Development and optimization studies of a 3D radiochromic plastic dosimeter - Part 2**  
   By Adamovics, J.; Guo, P.; Burgess, D.; Manzoor, A.; Oldham, M.  
   In a previous study, 7 different transparent plastics were evaluated as dosimeter matrixes along with 6 different leuco dyes as the radiochromic agent. Polyurethane along with the triphenylmethane, leucomalachite green, are the optimal combination of the formulation variables studied. The dosimeter sensitivity and post irradn. stability of an addnl. plastic matrix and 5 different leuco dyes were examd. Two formulations exhibit the most future promise for practical use in 3-dimensional dosimetry with respect to their initial sensitivity and stability.

44. **A new approach to radiochromic three-dimensional dosimetry-polyurethane**  
   By Adamovics, J.; Maryanski, M. J.  
   Three-dimensional dosimeter material was produced from a diisocyanate and a polyl to form a polyurethane matrix that contained radiochromic dyes in the leuco-form and free radical initiators. The dyes could be tri-Ph methanes, spiropyrans, chromenes, oxazines, phenazines, phthalides, fluoranes, tetrazoles, and polydiacetylenes. Org. peroxides, halocarbons, azo, carbonyl and sulfur compds. could act as free radical initiator. Irradn. induced free radicals that oxidized the leuco-dye, and after radiolytic oxidn. the dye exhibited absorbance in the visible range.

45. **Enhanced Performance of PRESAGE - Sensitivity, and Post- Irradiation Stability**  
   From Med. Phys. 32, 2004 (2005); SU-FF-T-239  
   By J Adamovics, J Dietrich, K Jordan,  
   Purpose: To improve the dose sensitivity and to control the post-irradiation radiochromic response of PRESAGE™ a 3D dosimeter. Method and Materials: One cm plastic cuvettes were filled with formulations of PRESAGE™ that varied in the composition of leuco malachite green(LMG), a radical activator and a dissolution solvent. The dosimeters were irradiated using a Varian 600C linear accelerator with a 4 MV photon beam. The dosimeters were irradiated at doses ranging from 10cGy to 60Gy (250 cGy/min) and
measured on a Hitachi-Perkin Elmer 204 spectrometer at 630 nm. The absorbances were measured 10 minutes after irradiation and up to a week post-irradiation. The sensitivity of PRESAGE™ to room light was investigated by placing dosimeters in a laboratory under constant room light at 22°C for approximately 6 hr and periodically measuring the radiochromic response. Results: The radiochromic response at 630 nm was linear from 0 to approximately 30 Gy with a slope of 0.16 OD/Gy and with an error, R2, of 0.9995. The lower limit of dose measurement of the dosimeter is 10cGy. The stability of the post-irradiation radiochromic response can be varied with minor detectable radiochromic response loss after 7 days (<1%/24 hr) to nearly 100% loss of radiochromic response 24 hr. When exposed to room light the photochromic background increases 0.05 cm-1/hr. Conclusion: The performance characteristics of PRESAGE™ have been enhanced by increasing the sensitivity of the dosimeter. The rate of thermal bleaching post-irradiation can be controlled by varying the ratios of the LMG to the radical activator and quantity of dissolution solvent. The ability to control the rate of losing the radiochromic dose distribution is an important characteristic for a potentially reusable dosimeter. Precautions must be taken to minimize the exposure of PRESAGE™ to room light.

This invention relates to a method of forming a three-dimensional (3D) dosimetric map in a solid translucent or transparent polymer and to an article of manuf. comprising a polymer formulated to capture data imparted by incident penetrating radiation. The present invention provides a method of prepn. of a solid translucent or transparent polymer matrix capable of detecting and displaying a dose or doses of penetrating radiation by forming within the polymeric matrix a 3D dosimetric map, which is measurable and quantifiable by various known procedures.

47. OCT Scanning Properties of PRESAGE - A 3D Radiochromic Solid Polymer Dosimeter
By J Adamovics, M Maryanski
PRESAGE™ is a new type of 3D dosimeter composed of clear rigid polyurethane and the radiochromic leuco dye, leucomalachite green. In the polyurethane matrix the leucomalachite green has a maximum absorbance at 633 nm and is therefore compatible with the OCT-OPUS™ laser CT scanner (MGS Research, Inc., Madison, CT) operating at the principal He-Ne laser wavelength of 633 nm. One inherent advantage of PRESAGE™ is that it does not need to be held in a container, which eliminates the need to match the refractive indices of a container wall and the polyurethane dosimeter. The refractive index of PRESAGE™ is ca. 1.515, which is matched for OCT scanning with a mixture of organic phthalates. OCT scanning of PRESAGE™ dosimeters has detected doses on the order of 50 cGy. The two areas that need additional study and are detected during OCT scanning are the variability of the refractive index across the polymer and polymer heterogeneities. The possible causes and consequences of these variations will be presented.

48. New 3D Radiochromic Solid Polymer Dosimeter From Leuco Dyes and a Transparent Polymeric Matrix
By J Adamovics, M. J. Maryanski
From Medical physics (2003), 30(6) SU-GG-PDS-29
A new type of solid radiochromic 3D polymer dosimeter has been developed. Components include an alkyl diisocyanate prepolymer, a hydroxy reactive polyol along with a catalyst, which polymerize into an optically clear polyurethane. The diisocyanate and polyol are mixed at approximately a 1:1 ratio with relatively low reaction exotherm, which allows the mixing of a wide variety of heat sensitive leuco dyes and free radical and/or acid generators into the polymer reaction matrix. The polymer hardens in approximately 48 hours so that no container is needed to support the dosimeter. The leuco dyes in our
dosimeters (leucomalachite green) have a maximum absorbance at 633 nm and is therefore compatible with the OCT-OPUS® laser CT research scanners (MGS Research, Inc., Madison, CT) operating at the principal He-Ne laser wavelength of 633 nm. We have demonstrated that this dosimeter formulation has characteristics required of a reliable dosimetry technique. Samples contained in 30 ml glass vials were irradiated to graded doses of 145 kVp x-rays and optical absorption spectra of the irradiated samples were measured. In one formulation, the sensitivity of the polymer at 633 nm was found to be 0.01 cm⁻¹ Gy⁻¹ between 1 Gy and 30 Gy. The sensitivity can be controlled by changing the proportions of the polymer’s components. Additional data on accuracy, stability, dynamic range, sensitivity control, dose rate effects, optical properties and tissue equivalence of the dosimeter will be presented.