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# Review of four novel dosimeters developed for use in radiotherapy

P Metcalfe

*University of Wollongong, metcalfe@uow.edu.au*

A Quinn

*University of Wollongong, aq908@uowmail.edu.au*

K Loo

*University of Wollongong, kjjl104@uowmail.edu.au*

M Lerch

*University of Wollongong, mlerch@uow.edu.au*

M Petasecca

*University of Wollongong, marcop@uow.edu.au*

*See next page for additional authors*

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# Review of four novel dosimeters developed for use in radiotherapy

## **Abstract**

Centre for Medical Radiation Physics (CMRP) is a research strength at the University of Wollongong, the main research theme of this centre is to develop prototype novel radiation dosimeters. Multiple detector systems have been developed by Prof Rosenfelds' group for various radiation detector applications. This paper focuses on four current detector systems being developed and studied at CMRP. Two silicon array detectors include the magic plate and dose magnifying glass (DMG), the primary focus of these two detectors is high spatial and temporal resolution dosimetry in intensity modulated radiation therapy (IMRT) beams. The third detector discussed is the MOSkin which is a high spatial resolution detector based on MOSFET technology, its primary role is in vivo dosimetry. The fourth detector system discussed is BrachyView, this is a high resolution dose viewing system based on Medipix detector technology.

## **Keywords**

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## **Disciplines**

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## **Authors**

P Metcalfe, A Quinn, K Loo, M Lerch, M Petasecca, J Wong, N Hardcastle, M Carolan, J McNamara, D Cutajar, I Fuduli, A Espinoza, C Porumb, and Anatoly B. Rosenfeld

## Review of four novel dosimeters developed for use in radiotherapy

**P Metcalfe<sup>1,2</sup>, A Quinn<sup>1,2</sup>, K Loo<sup>1</sup>, M Lerch<sup>1</sup>, M Petasecca<sup>1</sup>, J Wong<sup>1</sup>, N Hardcastle<sup>1,4</sup>, M Carolan<sup>1,3</sup>, J McNamara<sup>1,3</sup>, D Cutajar<sup>1</sup>, I Fuduli<sup>1</sup>, A Espinoza<sup>1</sup>, C Porumb<sup>1</sup> and A Rosenfeld<sup>1</sup>**

<sup>1</sup>CMRP, University of Wollongong, NSW, Australia.

<sup>2</sup>Liverpool Cancer Therapy Centre, NSW, Australia

<sup>3</sup>Illawarra Cancer Care Centre, NSW, Australia

<sup>4</sup>Peter MacCallum Cancer Centre, Vic, Australia

E-mail: metcalfe@uow.edu.au

**Abstract.** Centre for Medical Radiation Physics (CMRP) is a research strength at the University of Wollongong, the main research theme of this centre is to develop prototype novel radiation dosimeters. Multiple detector systems have been developed by Prof Rosenfelds' group for various radiation detector applications. This paper focuses on four current detector systems being developed and studied at CMRP. Two silicon array detectors include the magic plate and dose magnifying glass (DMG), the primary focus of these two detectors is high spatial and temporal resolution dosimetry in intensity modulated radiation therapy (IMRT) beams. The third detector discussed is the *MOSkin*<sup>TM</sup> which is a high spatial resolution detector based on MOSFET technology, its primary role is *in vivo* dosimetry. The fourth detector system discussed is BrachyView, this is a high resolution dose viewing system based on Medipix detector technology.

### 1. Introduction

In recent years linear accelerator and brachytherapy systems utilised for radiotherapy have improved to enable the delivery of increasingly complex dose distributions that conform tightly to the cancer treatment target. These developments have not been accompanied by vendors updating and supplying sophisticated on-board dose monitoring systems. For example linear accelerator vendors still rely on dual ion chamber assemblies with monitor unit and symmetry feedback only. These chambers are placed well above the collimation system and multi-leaf collimators (MLCs) in a position where they provide no feedback about the complex modulated dose distribution that exits the MLC.

### 2. Methods

#### 2.1. Commercial dosimetry array detectors

The requirement to produce dosimeters that can validate these complex modulated dose distributions has produced a myriad of pre vivo in phantom dosimetry test devices. These tests usually consist of a dosimetry phantom system. Some commercial examples include Delta4PT® which consists of two perpendicular diode arrays, ArcCHECK® which consists of a cylindrical diode array, and OCTAVIOUS® which houses a rotating array.



All these detector systems are placed in the treatment field before the first patient treatment fraction. The treatment plan is delivered to the dosimetry phantom system and the resulting dose map is compared with the radiotherapy treatment planning (RTP) computer dose map. In essence this is a pre-treatment test to ensure that the dose, segment and monitor unit information has been correctly transferred to the linac verification and MLC control system. These systems also test that the MLC positions are reasonably close to that planned.

Currently these methods do not account for any deviations in leaf consistency at each treatment fraction and hence the race is on to produce a system that can ascertain patient dose during each treatment fraction.

### 2.2. Magic Plate

The obvious positions to place this device are in the block tray (e.g. magic plate, Delta4 AV®) or behind the patient (EPID). The advantage of the EPID is it acquires the dose map after the beam has exited the patient and hence does not perturb the beam prior to the beam entering the patient. Most EPIDs have an amorphous silicon detector of very high spatial resolution. Some disadvantages are that the patient perturbs the beam. Another disadvantage is that most scintillation material currently used is of high atomic number so various corrections are required to account for beam energy off axis [1]. There is continuing research into the use of these detectors in direct mode<sup>1</sup> and perhaps low atomic number scintillators may be another option.

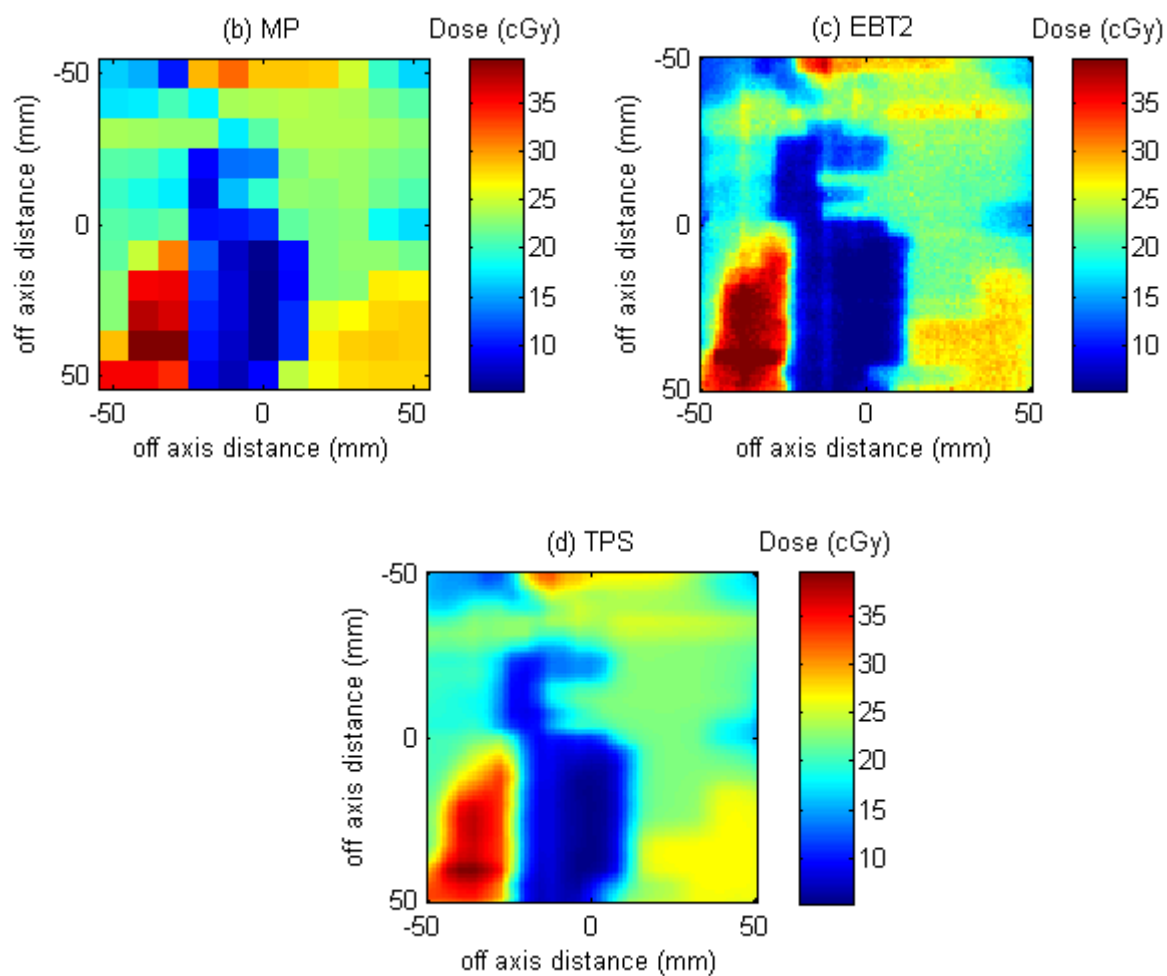
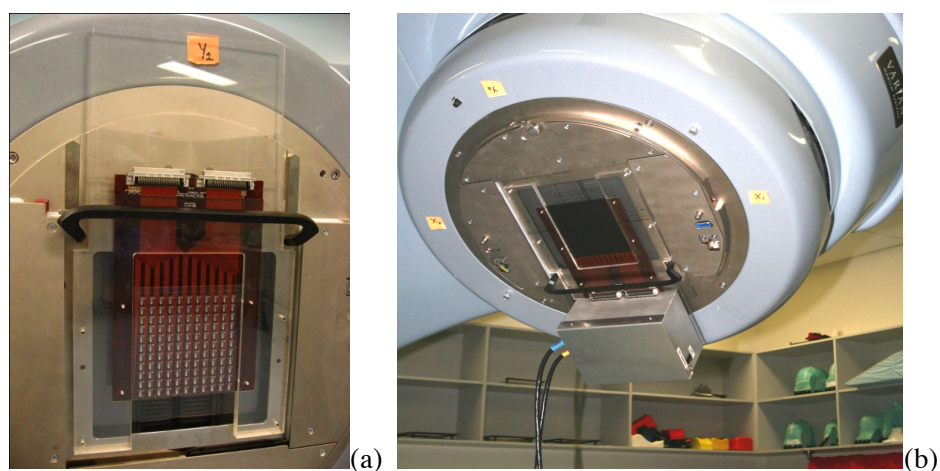
Dosimeters that are placed in the block tray seem a logical choice. The CMRP version of this concept consists of a series of epitaxial silicon diodes. The system is so named the Magic plate. Important characteristics of these detectors are that they do not reduce the beam transmission significantly (preferably <1%). Also their electron contamination contribution should not extensively alter the patient skin dose. Many of these detectors also consist of discrete detector elements, so they are constrained by the Nyquist criteria in terms of spatial resolution, in particular with regard to pitch between each detector array element. Placing these detectors in the block tray without full build up basically turns them into a fluence detector. While angular response becomes a small issue as the detector array is virtually perpendicular to the beam. The spectral properties of the beam off axis just beneath the MLC is not well characterised by Monte Carlo calculations.

The Magic Plate generation 1 prototype tested was a 2D array of 11 × 11 silicon diodes covering an area of 10 × 10 cm<sup>2</sup> (figure 1a). The diodes were mounted on a 0.5 mm thick Kapton substrate using the 'drop-in' technology. The physical size of a single diode is 1.5 × 1.5 × 0.425 mm<sup>3</sup>. The Magic Plate was designed to be mounted on the linear accelerator head (accessory mount slot) in line with the radiation beam (figure 1b). It is designed to operate as a transmission detector measuring the 2D fluence map of the modulated radiation beam [2].

The diodes that was used in the Magic Plate was grown using the epitaxial-growth technique [3]. For the MP diodes, the p-epitaxial layer is a 50 μm thick p-Si grown on top of a 375 μm thick high resistivity p<sup>+</sup> substrate. The sensitive volume of the individual element defined by the n<sup>+</sup> region is 0.5 × 0.5 × 0.05 mm<sup>3</sup>, whilst the detector pitch is 1 cm. The next prototype will have more detectors packed more closely. The number of detectors is limited by, packing density and readout capability (channels). Also detectors can be packed more closely if smaller fields such as Stereotactic radio-surgery (SRS) fields are to be studied. CMRP are currently working on a miniature SRS mobile tracking version of this detector.

### 2.3. Dose Magnifying Glass

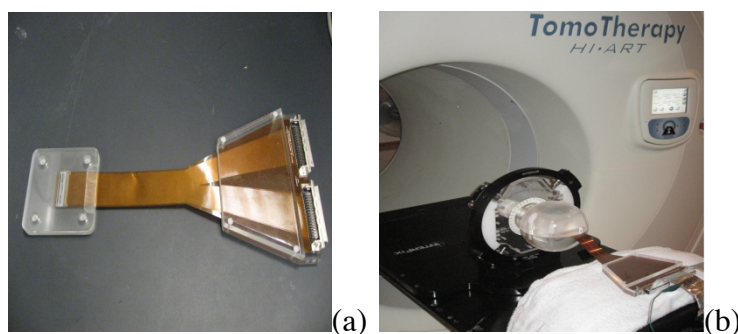
The CMRP have developed a silicon strip detector that has very high 1D spatial resolution at very high temporal resolution. The device is called a Dose Magnifying Glass (DMG). The 1<sup>st</sup> generation device had a ceramic base, however for the 2<sup>nd</sup> generation DMG is mounted on Kapton (Atomic number Z=6.6 and mass density= 1.45g/cm<sup>3</sup>). The thickness of the Si wafer is 375 μm and the strip pitch is 200 μm. The silicon strips are 20 × 2000 μm<sup>2</sup>. The device has been found to be useful in measuring radiation fields that have rapid dose and time varying gradients.



(c)

**Figure 1:** The CMRP Magic Plate Prototype 1(a) close up view, (b) mounted on linac head block tray, (c) intensity modulated radiotherapy (IMRT) dose maps, magic plate (left), Gaf film (middle), Pinnacle® RTP (right).

We have reported the use of this device to track linac IMRT dose depositions - see Wong et al [4]. The device has also been reported in SRS small field dosimetry [5]. The DMG has also been used to measure Tomotherapy binary leaf speed [6].



**Figure 2:** The DMG with Kapton base. (a)The silicon strip detector is shown in the Perspex on left and the pig tail out to readout is shown on the right. (b) DMG placed in Lucy Phantom for Tomotherapy™ SRS measurements.

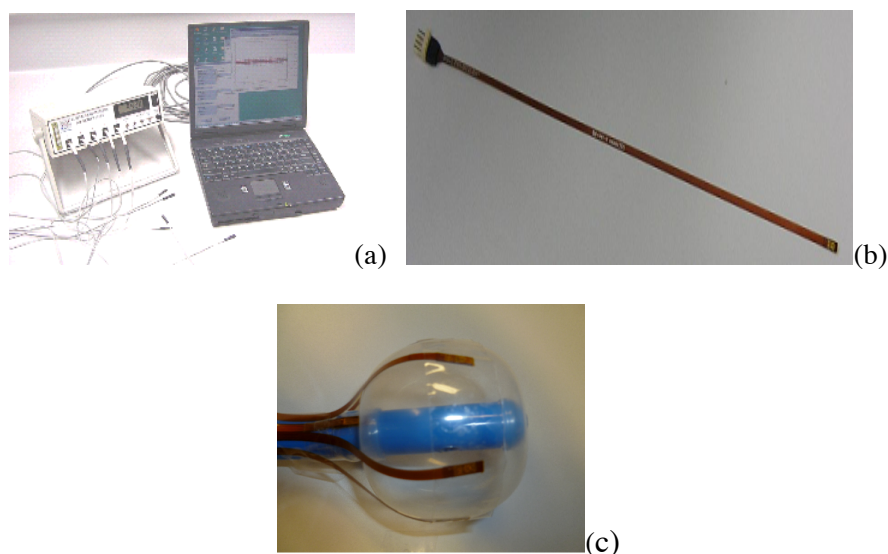
### 2.3. *MOSkin™ In Vivo Dosimeter*

The *MOSkin™* is a metal oxide semiconductor field-effect transistor (MOSFET) - based radiation detector that has been developed to provide real time on-line *in vivo* dose measurements during radiation therapy. MOSFET-based radiation detectors use a single transistor to measure the radiation dose through the trapping of electrical charges within the transistor structures. Transistors are fabricated to be very small and to feature micron-sized radiation-sensitive structures; thus, these devices are ideal for measuring the radiation dose in areas of high-dose gradient, where the size of the detector may affect the reading. The *MOSkin™* is mounted beneath a thin plastic cover with a uniform thickness that has been engineered to provide a depth of measurement of 0.07 mm, giving a skin dose equivalent depth when placed on a surface during radiation therapy [7].

The *MOSkin™* detector is operated through a data collection unit, which can read out five devices at once in real time. Multiple data collection units may be used to operate more devices, and these may be connected to a computer for real time software-based analysis, see Figure 3.

The *MOSkin™* detector has been successfully deployed to measure skin dose from conventional linear accelerators. Dose from megavoltage (MV) and kilovoltage (kV) image guidance devices has also been measured. The *MOSkin™* device has a 2.5 mV cGy<sup>-1</sup> sensitivity to MV X-rays, and an 8 mV cGy<sup>-1</sup> sensitivity to kV X-rays (~100 kVp), the difference is attributed to the detectors enhanced sensitivity to the photoelectric effect. We have reported using these devices to assess skin dose during breast radiotherapy with immobilisation cast material [7]. Additionally the in-field and out-of-field skin dose has been measured for various image guidance and treatment scenarios involving breast tangents [9].

The *MOSkin™* detector has been deployed for intra-cavity dosimetry during brachytherapy and external beam radiation therapy [10]. The design of the detector allows for the placement of the radiation-sensitive volume against the cavity wall, providing point-dose measurements on the cavity surface. Current work, which will be discussed, includes the continuing development of the devices with endo-rectal balloons (ERBs) in order to assess *in vivo* rectal wall dose during prostate external beam radiotherapy. Hardcastle *et al* showed that the *MOSkin™* device may be integrated with an ERB to provide point-dose measurements from multiple locations of the rectal wall in real time during radiation therapy [11]. The ERB restricts motion of the rectum during irradiation and holds the dosimeters firmly against the cavity wall.



**Figure 3:** MOSkin™ Detector System: (a) read out device, (b) MOSkin™ detector on Kapton pigtail, and (c) multiple MOSkins™ mounted on a Endo Rectal Balloon (i.e. The Octo MOSkin prototype).

An *in vivo* dosimeter placed on the anterior rectal wall allows the clinician to measure the dose delivered to the section of the rectum receiving the highest dose. This is important where high doses are delivered to the residual prostate and anterior rectal wall, and would be particularly useful in the context of the limitations of dose calculation algorithms at cavity interfaces. Accurate knowledge of the rectal wall dose is needed to identify the relationship between the dose delivered and rectal toxicity. A secondary application of an *in vivo* anterior rectal wall dosimeter is target dose verification. The anterior rectal wall is generally contained within the planning target volume (PTV); therefore, any dosimeter placed on the anterior rectal wall can be used as a surrogate for the PTV dose at the posterior region of the volume. Recent articles have focused on implantable *in vivo* dosimeters for target dose verification [12-14]. It is less viable to implant these dosimeters in the post-prostatectomy setting, and is less invasive to use the MOSkin™ dosimeter mounted on an ERB. Furthermore, MOSkins™ are visible on CT. This ensures precise positioning of the dosimeter so that the dose can be compared with a dose-point calculation using a RTP computer. The application of the MOSkin™ to analyse the dose to the anterior rectal wall in the high-dose gradient region has been assessed [15]. The devices to be deployed in a proposed future study will be used in an eight-detector Octo-MOSkin configuration to track dose points around the rectal and anal wall interface.

#### 2.4. BrachyView

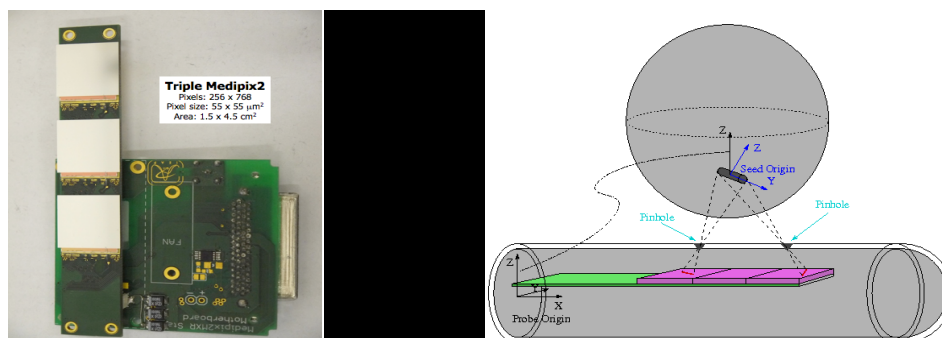
The traditional pre-planning technique for I 125 Brachytherapy seed or I-192 implants relies primarily on transrectal ultrasound (TRUS) imaging and has limitations that may be overcome by intraoperative dynamic treatment planning (ITP).

An innovative pixellated detector integrated within the TRUS probe for real-time and in-vivo seed and anatomical imaging has been designed at CMRP. The dosimetry system, named BrachyView, is capable of providing accurate intraoperative planning and post-implant verification.

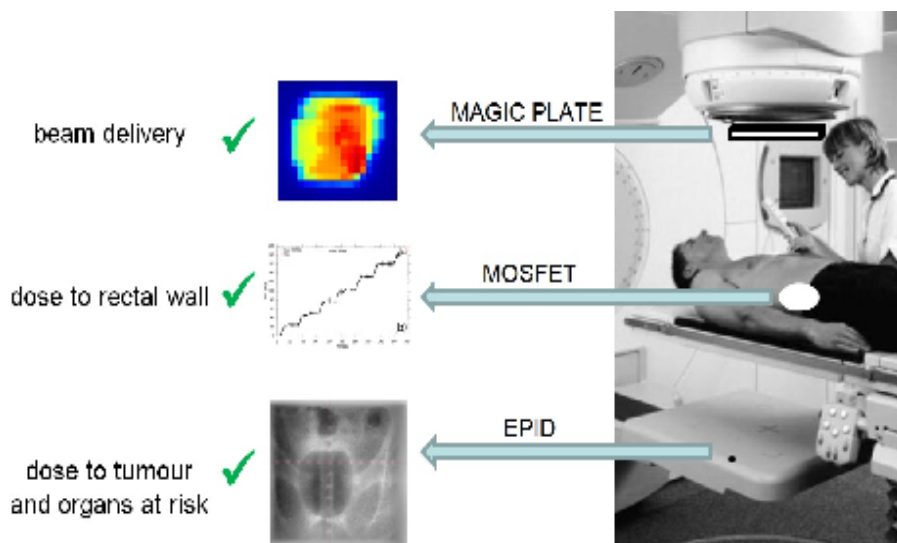
BrachyView incorporates three tiled Medipix2 detectors with a combined imaging area of  $14 \times 52 \text{mm}^2$  (256x768 pixels, each with size  $55 \times 55 \mu\text{m}^2$ ), coupled to a multi-pinhole collimator as shown in figure 5. The Medipix design is a high resolution, highly pixellated silicon-based detector with properties ideally suited for obtaining radiation events from the implanted I-125 seeds, or in the case of HDR brachytherapy, Ir-192 implants. Three-dimensional reconstructed positions from multiple planar images are used to resolve the seed placement in real time.



Feasibility studies of the BrachyView system with simple seed arrangements show it can provide dynamic information about seed positioning. Further steps, including software development for imaging of multiple seeds in a realistic clinical scenario are underway. The eventual integration of Medipix in the TRUS probe will also open up the possibility of CT imaging for post-implant dosimetry, thereby streamlining the entire implant into a single-room procedure, where a single device has the capabilities to perform prostate volume studies, intraoperative planning, and post-implant dosimetry.



**Figure 4:** The BrachyView Dosimetry system (a) close up view of triple medipix detectors and electronics (b) Schematic of BrachyView Seed Origin verification



**Figure 5:** Concept Diagram showing how Magic plate, MOSkin™ and EPIDs may be used in future to validate IMRT dose delivery courtesy P. Vial (Private communication).

### 3. Summary

Four of the myriad of radiation dosimetry systems being developed at CMRP has been discussed. The common theme that develops during testing all these devices is that spatial, energy, and temporal resolution are important characteristics that need to be assessed for the successful implementation of any new dosimetry system.

Despite several established models, EPID-based transit dosimetry remains an untapped potential for a variety of reasons [16]. In recent years, the exciting possibilities of EPID *in vivo* dosimetry have been demonstrated with EPIDs combined with daily kV-CBCT to reconstruct the dose in three dimensions to verify hypofractionated rectal cancer treatment [17]. It would be an exciting prospect to combine the use of EPID with an incident fluence detector (e.g. magic plate) and an *in vivo* detector



(e.g. MOSkin™) to give a detailed picture of dose at exit of the linac, dose at patient target and dose after exiting the patient.

Figure 5 illustrates a concept of how future patient treatments may be verified. A treatment plan may be compared with the reconstructed dose of the day and used in three-dimensional dose-comparison metrics to identify differences [18, 19].

Testing new detectors at CMRP is a bit like being a taste tester at a chocolate factory, some of the samples don't taste good to start with and may require some modifications to the recipe, but when a good prototype arrives that works well then that tastes real sweet.

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