Scintillators for 3D and 4D dosimetry: current status and future potential for clinical translation

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Abstract. New radiotherapy treatment techniques make unprecedented demands on dosimetry. Water equivalence, radiation hardness, high temporal and spatial resolution in 4D are no longer desirable but essential for safe implementation of several techniques. Plastic scintillation dosimetry has the capabilities to meet all of the above criteria. Despite several attempts, a system has not yet been commercialised for widespread availability in the clinic. Successful translation of good science to the benefits of clinical practice demands that the primary focus be shifted from the technological innovation to the patient needs. We will present the clinically beneficial features of scintillation dosimetry and some remaining challenges. Then we will discuss the barriers to widespread availability of scintillation dosimeters.

1. The Problem: unmet needs in clinical dosimetry
New treatment approaches have placed additional demands on clinical dosimeters. As an example, small field and dynamic composite treatments are now mainstream in contemporary radiotherapy practice, however, the dosimetry of these fields is often difficult. It is argued that this is due to the lack of lateral electron equilibrium for fields below 30 mm [1] and that the measurements of non-water equivalent dosimeters is affected by the detector density [2]. Insufficient care with dosimetry of such fields could substantially affect the quality of radiotherapy treatments (Figure 1).

![Figure 1: Radiation dose distribution calculated in iPlan for a trigeminal neuralgia, treated with a 4mm cone on the Varian Novalis linear accelerator. The dose profile prescribed to is based on measurements using a PTW 60012 diode, while the delivered dose (dotted line) is determined from scintillator detector measurements. The difference in the measured dose on the central axis is 13%.

Although correction factors for non-water equivalent dosimeters used in small radiation fields have been published [3, 4], Scott et al [2] argues against their use, suggesting a better approach would be to...
manufacture small-field relative detectors with small active volumes and a density similar to water. Scintillation dosimetry offers a solution with plastic scintillators, which have a water equivalent response in megavoltage beams.

2. A Solution: scintillation dosimetry

The concept of scintillation dosimetry involves capturing the light from a scintillator with an optic fibre and measuring its magnitude with a photodetector. The measured light signal is proportional to the rate of deposition of ionizing radiation energy in the volume of the scintillator. While conceptually simple, the choice of scintillator, optic fibre and photodetector can affect the performance of the dosimeter and each component needs to be optimised for the dosimeter’s specific application [5, 6].

Historically, the clinical uptake of scintillation detectors in external beam radiotherapy has been complicated by the unwanted generation of Cerenkov radiation at megavoltage energies. In the megavoltage beam of a linear accelerator, Cerenkov light background is generated in the optic fibre used to transport the scintillation signal to the photodetector. Several methods have been proposed to account for the Cerenkov signal. These methods include: the use of a parallel background fibre to estimate the Cerenkov radiation in its partner [7]; utilizing spectral differences between scintillation and Cerenkov light [8, 9]; separation using temporal differences in the prompt generation of Cerenkov light and the delayed generation of scintillation light [10, 11]. A recent successful approach is the use of an air core dosimeter, Figure 2 [12, 13].

![Figure 2: (A) a fibre optic dosimeter (FOD) and (B) an air-core FOD.](image)

These methods have all been shown capable of obtaining an accurate measurement of dose in megavoltage beams, promoting scintillation dosimeters as an effective point dosimeter in external beam therapy. For example, in the measurement of relative output factors in water ($S_p$), scintillation dosimeters have excellent agreement with ion chambers for field sizes 30 mm – 100 mm, and with radiochromic film down to 4 mm, Figure 3 [4].

![Figure 3: Relative output factors in water ($S_p$), measured with an air core scintillation dosimeter, ion chamber and radiochromic film.](image)
Plastic scintillators are water equivalent, angle and dose rate independent. Furthermore their small size minimizes volume averaging and as a result, scintillation dosimeters can be seen as the ideal component to build high spatial and temporal resolution dosimeter arrays. We have carried out a successful clinical trial of an array of 16 FODs to measure, in real time, the dose to the rectal wall during a brachytherapy treatment (Figure 4), providing conclusive evidence of the clinical benefits.

Figure 5 shows a dose profile for an SRS field on a Varian Novalis linear accelerator, measured with an air-core FOD array, validated with radiochromic film. This array provides high speed data processing and progress towards a 4D scintillation dosimetry system is well underway.

3. Challenges to clinical implementation of scintillation dosimetry

For clinical availability, dosimeters need to be commercialised. To date the only fully commercialised dosimeter based on plastic scintillators has been the "Daily Constancy Tool" (Gammex model 444), in which the sensing element was coupled to a silicon photodiode via a short fibre [15]. Due to inadequate clinical performance the scintillator was replaced with a silicon detector. A 2D scintillating dosimeter DosiMap [9] using spectral discrimination was specifically designed for IMRT QA. DosiMap made strong progress towards clinical translation, however it did not become available to the
clinical community. Recently, Standard Imaging have promised a single point scintillation dosimeter, using photodiodes for readout in the linac bunker. Lack of commercialisation success emphasises the importance of fully evaluating the performance of the materials and technology in a routine clinical environment before going to market with a device. Any proposed device must be subjected to a trial under clinical rather than laboratory conditions. Reproducibility of the system day to day, sterilisation capability and temperature dependence (for in-vivo), hospital cleaner hardness, immediate response (no warm up), radiation hardness, intuitive interface and ergonomic handling and set up of the device are all important along with dosimetric accuracy, which has been the main focus to date.

4. Conclusion
Radiation dosimeters must serve the radiotherapy treatment process and not vice versa. As the field of scintillation dosimetry matures with several groups introducing innovative and exciting applications, it is timely for clinical physicists to engage in developing the applications which best serve currently inadequately met clinical dosimetry needs.

5. References
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