RSC: Optically stimulated emission of LiF:Mg,Cu,P - towards 3D optically stimulated luminescence dosimetry

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Abstract. With the introduction of highly conformal treatment modalities, dose verification in 3D is becoming more important than ever for patient-specific quality assurance of radiotherapy. Reusability of 3D dosimeters may be the path to cope with the cost-benefit issues caused by batch-to-batch fluctuations and intense calibration protocols in existing 3D systems. We present the idea of an envisioned (optically stimulated luminescence) OSL-based 3D readout system, which exploits the inherently reusable dosimetry properties of OSL. We provide the emission spectra of the OSL active material LiF:Mg,Cu,P (MCP) for three stimulation wavelengths (460 nm, 532 nm, and 664 nm), and summarize recently published optical characterization results to highlight the requirements of a readout system for an MCP-based dosimeter.

1. Introduction

Research in 3D dosimetry has been of great interest during the past decades [1-4]. The well-established need for 3D dosimetry becomes continuously more relevant as highly conformal radiotherapy modalities are utilized worldwide [2-7]. At the time of writing, multidimensional arrays of ion chambers and diodes are clinically used as semi-/pseudo-3D dosimeters, while true 3D dosimeters are mainly used at research institutes [3]. Thus, a widespread introduction of clinically accepted (true) 3D-dosimetry systems still lies ahead. Key elements delaying the implementation of true 3D dosimetry in quality-assurance routines are the high-cost, batch-to-batch fluctuation, calibration, and lack-of-reusability properties shared by most 3D-dosimetry systems. Our group has previously presented the idea of an (optically stimulated luminescence) OSL-based 3D dosimetry system to overcome the reusability issue [8, 9]. With a reusable dosimeter, batch-to-batch fluctuations and tedious calibration protocols become much less important.

The envisioned OSL-based 3D dosimetry read-out system is outlined in figure 1, where a laser source provides the stimulation light from the left. The laser beam is first collimated, before it is transformed into a sheet of laser light by the combination of a Powell lens and a Fresnel lens. The plane of laser light is used to stimulate the composite dosimeter material sheet by sheet, providing the
third dimension by moving the dosimeter with a translation stage. The composite dosimeter material, placed on top of the translation stage, should consist of small particles of OSL-active material embedded inside a transparent silicone matrix as presented in [8]. The stimulation of OSL-active particles will yield a dose-dependent OSL emission. The use of imaging optics and spectral filters in front of a camera will allow the acquisition of a series of dose-dependent 2D images of the stimulated sheets of the 3D dosimeter.

A potential OSL material for the 3D dosimetry system presented in figure 1 is the near-tissue-equivalent LiF:Mg,Cu,P (MCP) with $Z_{\text{eff}} = 8.2$. MCP is best known for its TL properties but has also been investigated for its OSL properties in recent years [10-13]. Here, we present the emission spectra of MCP for three different stimulation sources. We also summarize dose-response and emission-intensity results presented in [13]. Emission spectra allow the identification of necessary equipment for a readout system, e.g. spectral filters. Dose response and emission-intensity information provides an estimate of the measurable dose-region, where the upper limit is characterized by a small deviation from linearity. Such deviation can be found by a saturation curve fit of the type $S = S_0 \left(1 - e^{-D/D_s}\right)$ [14-16], where $D_s$ indicates a dose with $\sim 37\%$ lower dose response than for a linear behaviour.

2. Materials and methods
MCP emission was measured under truncated-Gaussian-continuous-wave stimulation by 460 nm (blue), 532 nm (green), and 664 nm (red) lasers. Wavelength-dispersed emission was monitored by a CCD sensor (PIXIS 100BR) attached to the back of a spectrometer (Princeton Instruments Acton SP2358). Several wavelength regions were measured using a combination of spectral filters. All samples were irradiated by 20(1) Gy water-equivalent dose with a Cs-137 gamma source. Measurements were acquired 10 to 40 minutes after radiation.

3. Results and discussion
The emission of MCP shown in figure 2 shows the spectra under blue (460 nm), green (532 nm), and red (664 nm) stimulation respectively. The decaying OSL signal is seen between 340 nm and 400 nm for the blue stimulation, between $\sim$ 400 nm and 470 nm for the green stimulation, while no decaying OSL emission is observed for red stimulation, as previously demonstrated [13]. It is observed that all three emission spectra show a steeply increasing anti-Stokes shifted signal from the pump laser with its wavelength located in the filtered region. All stimulation wavelengths show an intense emission in the region for wavelengths higher than the stimulation wavelength.

As noted by Nyemann et al., the lack of OSL emission under red stimulation indicates a room-temperature activation energy of the OSL active dosimetric state above 1.85 eV. Similarly, it must be lower than 2.33 eV due to the observation of OSL for the green stimulation. The steep anti-Stokes shifted emission observed for all three stimulation wavelengths can be interpreted as a so-called Raman continuum [13, 17, 18]. The spectra presented here further support this interpretation, as all
three stimulation wavelengths produce somewhat similar characteristic emission (note that a direct comparison should be made on an energy scale). The long-wavelength regions (longer than the stimulation wavelength) are very similar for all stimulations with a clear indication of an emission band near 900 nm. The intensity of the long-wavelength emission emphasizes the need for efficient filtering of all other wavelengths than the OSL emission window, for any of the selected stimulation sources. It is also necessary to filter out the stimulation wavelength and the anti-Stokes shifted Raman continuum. For OSL readout with a blue stimulation source this means that spectral filters should be included at position 6 (see figure 1) to only allow transmission of emission below $\sim 400$ nm.

Similarly, the lack of OSL under red stimulation puts a clear upper limit on the wavelength of the stimulating laser (position 1) for the 3D readout system.

The dose response for the OSL emission of MCP under blue stimulation (340-400 nm) is shown in figure 3, with the OSL decay for the 10 Gy dose in the inset. This dose response has a sublinear behaviour where a saturation fit yields a saturation dose of 75(12) Gy, which at 10 Gy corresponds to a 6 % deviation from linearity. This suggests that doses below 10 Gy for MCP can easily be monitored when using appropriate calibration procedures [13].

The dose response at 10 Gy was by Nyemann et al. used to estimate the isotropic photon flux emitted by a cubic millimeter of MCP per Gy to be $3.3 \times 10^8$ photons / (Gy·mm$^3$) in the full solid angle of $4\pi$. This emission was used to estimate a minimum dose of approximately 0.1 Gy that can be measured with a S/N ratio of 50 for MCP particles embedded in a 3D-dosimeter at a 1 % concentration [13]. Assuming negligible contributions from systematic effects, the accuracy will be dominated by read-out precision, yielding an accuracy of a few percent. This shows that MCP has the potential to constitute the OSL-active material in a future 3D-dosimetry system with a measurable dose range of 0.1-10 Gy.
4. Conclusion

Optically stimulated luminescence processes are shown to be a reasonable pathway toward reusable 3D dosimeters. The emission spectra of MCP are presented for three different stimulation sources. It is shown that a stimulating laser for an MCP-based system must have a wavelength below 664 nm, and that a system based on a 460 nm laser must use filters that block emission > 400 nm efficiently. The OSL active material MCP is estimated to provide a measurable dose range of 0.1–10 Gy for an MCP-silicone 3D dosimeter.

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6. References

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