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TOPICAL REVIEW

Using the optically stimulated luminescence technique for one- and two-dimensional dose mapping: a brief review

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Abstract

In respect of radiation dosimetry, several applications require dose distribution verification rather than absolute dosimetry. Most protocols use radiological and radiochromic films and ionization chambers or diode arrays for dose mapping. The films are disposable which causes the precision of the results dependent on film production variability. The measurements with arrays of ionization chambers or diodes mainly lack spatial resolution. This review aims to provide an overview of the use of optically stimulated luminescence detectors (OSLDs) for one-dimensional (1D) and two-dimensional (2D) dose mapping in different applications. It reviews the ideas, OSL materials, and applications related to the assessment of dose distribution using OSLDs in the form of film or ceramic plate (BeO). Additionally, it reviews research published in the international scientific literature from 1998 to 2021. As an outcome, a table containing the main characteristics of each relevant paper is shown. The results section was divided by the type of OSL material, and we briefly described the principal findings and the significant developments of each mentioned study such as film production and OSL reader assembly. The purpose of this study was to present an overview of the main findings of several research groups on the use of OSLD in the form of film or plate for 1D and 2D dose mapping. Finally, the potential future development of dose mapping using OSLD films was outlined.

1. Introduction

Passive dosimetric systems that apply thermoluminescence (TL) and optically stimulated luminescence (OSL) techniques are widely used for occupational and environmental dose assessment programs, are also used for various dosimetric applications and, according to the American Association of Physicists in Medicine (AAPM) Task Group 191, are practical, accurate and precise for medical physics applications (Izewska *et al* 2003, ICRP 2007, Ramos *et al* 2015, Kry *et al* 2020).

The TL and OSL dosimeters are composed of radiation-sensitive detector materials that emit light with an intensity proportional to the radiation dose previously absorbed by the material when subjected to an external stimulus, thermal (TL) or optical (OSL) (Yukihara and McKeever 2011). Owing to the optical nature of the process, the OSL technique has various advantages over the TL technique.

The advantages of the OSL technique include simplicity of reading, as well as the possibility of reassessment of doses and measurement of accumulated and individual doses with the same detector (Gasparian *et al* 2010, Yukihara *et al* 2009, Yukihara and McKeever 2011, Malthez *et al* 2014, Sawakuchi *et al* 2014). Also, the use of light (from a LED, laser, or lamp), instead of heating, to read the detector overcomes the problems related to the temperature dependence of the luminescence efficiency (thermal quenching) (McKeever and Moscovitch 2003). The optical readout also allows the use of detectors made with plastic, for example, which can be used in different sizes and shapes (e.g. small detectors of 2 mm diameter or strips for dose profile measurement in computed tomography). The optical readout is also doubtless easier to control than the detector heating. Moreover, readout can be faster using OSL, because one can stimulate only the initial intensity of the OSL. In addition to fast readout, the stimulation of a small portion of the OSL signal allows multiple readouts of the detectors. Another advantage associated with the OSL technique is the detector reader. The OSL reader is relatively simple compared to a TL reader and can be small and portable, allowing fast readout on-site.

Currently, the main materials used with the OSL technique in commercial dosimetric systems are carbon-doped aluminum oxide (Al_2O_3:C) and beryllium oxide (BeO) (Yukihara *et al* 2014, Lalic *et al* 2019). The characterization of other materials that can be used with the OSL technique has been described in several scientific articles. Owing to the advantages of the OSL technique, various research groups have been working on the development of new OSL materials, including synthetic materials such as lithium magnesium phosphate ($LiMgPO_4$) and lithium aluminum oxide ($LiAlO_2$), and studying the luminescent and dosimetric properties of natural materials such as fluoride ore (Mittani *et al* 2008, Pradhan *et al* 2008, Twardak *et al* 2014, Wrobel *et al* 2014, Malthez *et al* 2018, Yoshimura and Yukihara 2006a, 2006b). In addition to material development, research groups are working on developing OSL detectors in the form of films for dose mapping applications.

In the past, OSL point detectors have been used for dose mapping however it is a time-consuming and complicated task to prepare, align in the radiation field, and to read the OSL signal of several small detectors keeping track of those. Also, the spatial resolution obtained is relatively poor and limited to the size of the detectors (Yukihara and McKeever 2011).

In addition to the already mentioned advantages of OSL, optical stimulation allows partial or localized reading of the material, contributing to the development of two-dimensional (2D) dosimetric systems. In principle, OSL area detectors can be produced in the form of film, and OSL 2D reader systems can employ optical guides, charge-coupled device (CCD) cameras, complementary metal-oxide-semiconductor (CMOS) cameras, or direct photomultiplier tubes (PMTs) for the detection of OSL signals. Recent studies demonstrated that OSL systems allow the evaluation of doses for 2D mapping in a relatively fast and simple manner, and the results indicate sub-millimeter resolution (Jahn *et al* 2013, Ahmed *et al* 2017, Martins *et al* 2020a).

Currently, the protocols for quality assurance and performance tests in radiology and radiotherapy employ detectors in film-shaped or 2D arrangements, such as radiochromic films and Dolphin systems based on a matrix of ionization chambers or diode arrays (Iba Dosimetry GMBH) (Devic IBA Dosimetr, no date2011).

Ionization chambers are the most established detectors for absolute dosimetry, however, they have a limited spatial resolution for dose distribution assessments and the same occurs with diodes mainly due to inevitable gaps between the detectors (Stelljes *et al* 2015, Fuduli *et al* 2016).

Radiological and radiochromic films have a high spatial resolution, which is essential for the verification of high-dose gradients. However, quantification of response variation depends on calibration, and the films are not reusable (Hartmann *et al* 2010). It requires calibration to be performed with one film and measurements with others so that the accuracy of the result is dependent on the variability of the production of the films. In addition, these films are commercially available at an exceedingly high cost, particularly in developing countries. However, the OSL technique often has the advantage of detector reusability. Thus, in principle, OSLD films can be easily acquired (at a relatively low cost) and reusable.

Considering the potential new materials and applications of 2D OSL dosimetric systems, in this study, we reviewed the scientific literature regarding the use of 2D OSL detectors (film and ceramic plate) in terms of the current state of development of 2D OSL systems and applications for radiation dosimetry.

2. Results

We reviewed 20 scientific research articles on OSL area detectors (OSLD films or BeO ceramic plates) specifically applied for dose-distribution assessment. Table 1 lists the papers and their respective details, organized according to the OSL material type.

Table 2 lists the main characteristics of the OSLD films (and BeO ceramic plate) reported in literature.

The application of an OSLD film depends mainly on the dosimetric properties of the detector material and the mechanical characteristics of the film matrix. For example, in diagnostic imaging applications, since the x-ray photon energy range is from a few keV to hundreds of keV, it is easier to apply an OSLD film with a relatively low effective atomic number, as the energy response is flatter in that range. However, energy dependence is not necessarily a limiting factor, since algorithms can be used for dose correction according to the energy response of the material to different types or energies of radiation. Likewise, it is not always possible to have a linear dose response for a wide range of doses, especially in high dose gradients, as in small fields in radiotherapy. It is important to evaluate the OSLD film dose response (for the radiation energy used) prior to the dose distribution mapping.

In the following subtopics, the main characteristics and findings of the studies on OSLD films (summarized in table 1) are presented. The subtopics are divided by type of OSL material and the film matrix adopted in each study is informed. Also, when possible, the disadvantages and limitations of the OSLD film are mentioned.

Table 1. Summary of published scientific articles on OSL area detectors (OSLD films and BeO ceramic plate) applied to 1D or 2D dose mapping. Included the year of publication, OSL material and form, proposed application, as well as the type of reader used.

Year	Material	Proposed application	Form	OSL reader type	Title and reference
2004	SrS:Ce,Sm	Intensity-modulated radiotherapy (IMRT) dose distribution verification	Laboratory produced film	Laboratory built OSL reader with LED and PMT	Quality Control of Intensity Modulate Radiation Therapy With Optically Stimulated Luminescent Films (Idri *et al* 2004)
2010	BeO	Various medical and industrial applications	Thermalox 995	BeOmax OSL System (Sommer *et al* 2007)	2D-OSL-dosimetry with beryllium oxide (Jahn *et al* 2010)
2011	BeO	Various medical and industrial applications	Thermalox 996	BeOmax OSL System (Sommer *et al* 2007)	Progress in 2D-OSL-dosimetry with beryllium oxide (Jahn *et al* 2011)
2013	BeO	Various medical and industrial applications	Thermalox 997	BeOmax OSL System (Sommer *et al* 2007)	The BeOmax system–Dosimetry using OSL of BeO for several applications (Jahn *et al* 2013)
2014	KCl:Eu	IMRT dose distribution verification	Laboratory produced film	Laboratory built OSL laser scanner	Two-dimensional high spatial-resolution dosimeter using europium doped potassium chloride: a feasibility study (Li *et al* 2014)
2007	Al_2O_3:C	RT applications	Luxel™	Landauer OSL reader	Optically stimulated luminescence (OSL) of carbon-doped aluminum oxide for film dosimetry in radiotherapy (Schembri and Heijmen 2007)
2009	Al_2O_3:C (1D)	CT dose profile	Luxel™	Laboratory built OSL reader	An optically stimulated luminescence system to measure dose profiles in x-ray computed tomography (Yukihara *et al* 2009)
2014	Al_2O_3:C and Al_2O_3:C,Mg	RT photon beam LINAC	Landauer prototype films	Laboratory built OSL laser scanner	Development of a 2D dosimetry system based on the optically stimulated luminescence of Al_2O_3 (Ahmed *et al* 2014)
2017	Al_2O_3:C and Al_2O_3:C,Mg	RT (megavoltage x-rays and ion beams)	Landauer prototype films	Laboratory built OSL laser scanner	Demonstration of 2D dosimetry using Al_2O_3 optically stimulated luminescence films for therapeutic megavoltage x-ray and ion beams (Ahmed *et al* 2017)
2020	Al_2O_3:C and Al_2O_3:C,Mg	MRgRT	Landauer prototype films	Laboratory built OSL laser scanner	Al_2O_3:C and Al_2O_3:C,Mg optically stimulated luminescence 2D dosimetry applied to magnetic resonance-guided radiotherapy (Shrestha *et al* 2020)
2017	BaFBr	IMRT dose distribution verification	Agfa prototype film	CR10-X Agfa HealthCare	A reusable OSL-film for 2D radiotherapy dosimetry (Crijns *et al* 2017)
2019	BaFBr	Extended-field radiotherapy (EFRT) dose distribution verification	Agfa prototype film	CR15-X Agfa HealthCare	Extended field radiotherapy measurements in a single shot using a BaFBr-based OSL-film (De Roover *et al* 2019)
2018	BaFBr (1D)	RT large field applications	Laboratory produced film	Laboratory built OSL and PL reader	Flexible optically stimulated luminescence band for 1D *in vivo* radiation dosimetry (Kim *et al* 2018)
2019	BaFBr:Eu^{2+} (1D)	Various applications	Laboratory produced film	Laboratory built OSL reader with LED stimulation	One-dimensional dose measurement with string-shaped photo-stimulated luminescence detector (Sato *et al* 2019)
2017	CaF_2:Ce	RT applications	Laboratory produced film	Laboratory built OSL reader	OSL films for *in vivo* entrance dose measurements (Souza *et al* 2017a)
2020	natural CaF_2	RT radiosurgery	Laboratory produced film	Laboratory built OSL reader	Validation of quality control in radiosurgery using OSL detector sheets based on Brazilian fluorite (Martins *et al* 2020b)
2019	$NaMgF_3$:Eu	RT applications	Laboratory produced film	CCD camera reader with LED stimulation	Development of a 2D dosimeter using the OSL of $NaMgF_3$:Eu with CCD camera readout (Schuyt and Williams 2019)

Table 1. (Continued.)

Year	Material	Proposed application	Form	OSL reader type	Title and reference
2020	LiF:Mg,Cu,P	RT applications	Laboratory produced film	CCD camera reader with LED stimulation	A new approach to the 2D radiation dosimetry based on optically stimulated luminescence of LiF: Mg, Cu, P (Sądel *et al* 2020a, 2020b)
2020	$LiMgPO_4$	Proton therapy applications	Laboratory produced film	fluorescent microscope with CCD camera	Two-dimensional radiation dosimetry based on $LiMgPO_4$ powder embedded into silicone elastomer matrix (Sądel *et al* 2020a, 2020b)
2020	MgB_4O_7:Ce,Li	RT applications	Agfa prototype film	Laboratory built OSL laser scanner	Feasibility studies on the use of MgB_4O_7:Ce,Li-based films in 2D optically stimulated luminescence dosimetry (Shrestha *et al* 2020)

Table 2. Summary of the main characteristics and dosimetric properties of the OSLD films reported in the literature.

OSL material	Reference	Dark fading of OSL signal	Type of radiation used	Dose response	*Z* effective
Al_2O_3:C	Ahmed *et al* (2017)	$<5\%\ yr^{-1}$	6 MV photons	Linear-exponential 0.02–70 Gy	11.3
Al_2O_3:C, Mg	Ahmed *et al* (2017)	uninformed	6 MV photons	Linear-exponential 0.02–70 Gy	Uninformed
BeO	Jahn *et al* (2010)	6% in 30 min and less than 1% in 6 months	MAXISHOT x-ray photons	Linear 10^{-6}–10 Gy	7.2
SrS:Ce,Sm	Idri *et al* (2004)	50% in 24 h	6 MV photons	Linear up to 10 Gy	14
KCl:Eu	Li *et al* (2014)	High fading	6 MV photons	Linear up to 60 Gy	18
BaFBr	Crijns *et al* (2017)	uninformed	6 MV photons	Linear up to 32 Gy	4.43
BaFBr:Eu^{2+}	Kim *et al* (2018)	20% in 20 min	6 MV photons	Linear up to 6 Gy	49
CaF_2:Ce	Souza *et al* (2017a)	uninformed	Beta particles	Linear 100–700 mGy	Uninformed
natural CaF_2	Martins *et al* (2020b)	uninformed	6 MV photons	Linear 1–20 Gy	Uninformed
$NaMgF_3$:Eu	Schuyt and Williams (2019)	40% in 24 h then stable	X-rays photons (40 keV)	Linear 1–100 Gy	10.39
LiF:Mg,Cu,P	Sądel *et al* (2020a, 2020b)	50% in 4 h	Beta particles and Cs-137 photons	1–100 Gy with a sublinear tendency	8.14
$LiMgPO_4$	Sądel *et al* (2020a, 2020b)	30% in 2 h	58.8 MeV protons	2–200 Gy Slight supralinear	Uninformed
MgB_4O_7:Ce,Li	Shrestha *et al* (2020b)	40% in 70 h	Beta particles	Linear up to 10 Gy	8.4

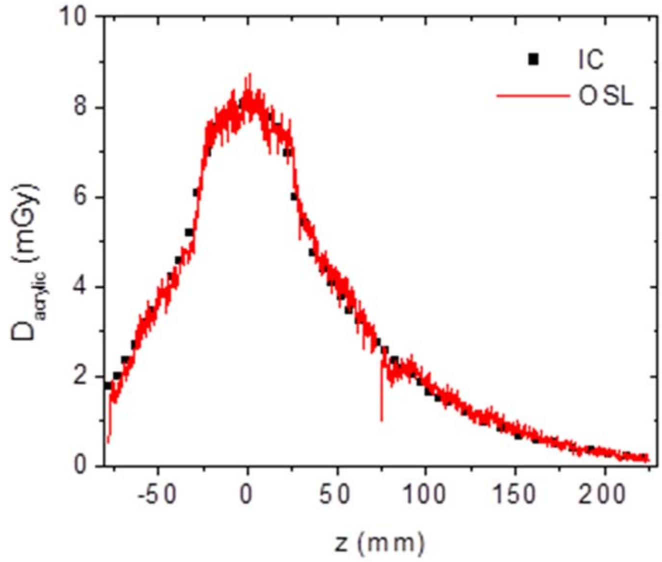

Figure 1. CT dose profiles for the central position of the phantom, which were acquired with a semiflexible ionization chamber (dots) and with OSL strip (line). The profile was obtained using two CT body phantoms; the second one shows the profile tail, due to scattered radiation. The peak voltage used was 100 kVp. The OSL dose was corrected for the aluminum oxide over response and is expressed in absorbed dose to acrylic (mGy).

2.1. Aluminum oxide OSLD film

Currently, carbon-doped aluminum oxide is the most commonly used dosimetric material with the OSL technique (Yukihara and McKeever 2011). Its applicability has been validated in different areas of dosimetry such as radiotherapy, environmental dosimetry, spatial dosimetry, and retrospective dosimetry (Mckeever *et al* 2004). Its advantageous dosimetric characteristics include relatively high sensitivity and linear OSL response with doses of up to approximately 10 Gy. However, it has some limitations, such as high density (3.85 g cm^{-3}) and an effective atomic number of 11.3, which leads to a response approximately four times greater for low-energy x-ray beams (20–30 keV). Another difficulty for some applications is the long luminescence lifetime (35 ms), which can be overcome using the pulsed OSL (POSL) technique. The low cross-section for neutrons is another difficulty that the development of detectors with the inclusion of neutron converters sought to solve (Yukihara and McKeever 2011).

Luxel^{TM} is a well-known detector used with the OSL technique and it is marketed by Landauer, Inc. It is a plastic tape (polystyrene) with a thin layer of carbon-doped aluminum oxide powder. This tape can be made available in roll form 15 mm wide and an active area thickness of 0.3 mm and then cut to the desired length. In general, Luxel^{TM} is used on 7 mm discs and it integrates the InLight microStar^{R} personal dosimetry system marketed by Landauer, Inc. Several studies in the literature describe the application of Luxel^{TM}.

First, Yukihara *et al* (2009) used Luxel^{TM} cut into strips (5 × 150 mm^2) for dose profile measurements on computed tomography (CT). They used an LED OSL reader developed in the laboratory with a motorized rail for the automated point-to-point reading of the Luxel^{TM} strip. They obtained CT dose profiles and CT dose index over an integration length of 100 mm ($CTDI_{100}$) values. These values differed by less than 5% compared to those obtained with a pencil-type ionization chamber under the same experimental conditions. Thus, they demonstrated the possibility of 1D OSL dosimetry in a relatively simple manner. Figure 1 shows a CT dose profile obtained with a Luxel^{TM} strip and a laboratory-built POSL reader.

Jursinic (2007) characterized the Luxel^{TM} disks for clinical dosimetric measurements and reported high precision and accuracy in measuring dose, that those have no dependence on irradiation angle, and can be read long after irradiation. In 2010, Jursinic (2010) reported that Luxel^{TM} presents a supralinear dose-response, regarding exposure to photons and that the response varied with accumulated dose. Schembri and Heijmen (2007) also tested the feasibility of the use of Luxel^{TM} in therapy with photon and electron beams. They used point measurements only and reported no or small response variations in the dose rate, beam quality, field size, and depth. They observed linear response from 0 to 200 cGy, which is a great advantage over radiochromic and gafchromic films. Yukihara *et al* (2008) reported no significant energy dependence of Luxel^{TM} disks for photon beams of 6 MV and 18 MV and electron beams of 6–20 MeV. Reft (2009) studied the response of the commercially available Luxel^{TM} in the function of energy, absorbed dose to water, and linear energy transfer (LET), aiming to provide additional information on the dosimetric properties and also to demonstrate the potential for their use in photon, electron, and proton radiotherapy dosimetry. The author reported a LET dependence on the relative response to 6 MV photons.

Furthermore, several other studies have evaluated the applicability of 1D OSLD based on Luxel^{TM}, as *in vivo* measurements in radiotherapy (Mrčela *et al* 2011) and characterization of the Landauer OSL nanoDot for dose measurements of patients in CT scans (Scarboro *et al* 2015).

In addition to Luxel^{TM}, which has been known for almost 20 years, other films have been produced experimentally by Landauer, Inc. One is equally composed of Al_2O_3:C and the other is composed of Al_2O_3:C, Mg (Ahmed *et al* 2014, 2016, 2017). Ahmed *et al* (2014) described that the difference is that the crystal grain sizes are smaller in the new films in comparison to Luxel^{TM}. According to Ahmed *et al* (2017), the OSLD film consists of a layer of 75 μm polyester and a layer of 47 μm aluminum oxide particles (grains of approximately 15 μm) in a binder. Landauer, Inc. produced a 125 μm thick 30 cm wide roll film. The authors mentioned that because of the use of smaller grains, the new film is significantly more homogeneous than Luxel^{TM}.

Ahmed *et al* (2014) described an OSL reader developed for 2D dosimetry using the new OSLD films based on aluminum oxide from Landauer, Inc. It is a scanner reader that uses a green laser (of approximately 100 mW power) for stimulation of the OSL signal, which in turn is detected by the PMT with a Hoya U-340 filter. They developed a correction algorithm to eliminate the effects of shallow traps and slow F-center luminescence lifetime of Al_2O_3:C. They demonstrated the possibility of using OSL from aluminum oxide films for 2D dosimetry.

Some characteristics of the 2D OSL system cited by the group (Ahmed *et al* 2017) include dose responses that are approximately linear-exponential to 6 MV linear accelerator photon beams from 20 to 70 Gy, no film saturation up to 76 Gy, minimum detectable dose less than 1 mGy, doses measured in agreement within 1% compared with measurements of the ionization chamber, and sub-millimeter spatial resolution. Comparing both films, the authors state that the image signal-to-noise ratio achieved using Al_2O_3:C, Mg films is better (~40%) than that obtained using Al_2O_3:C films because of the higher intensity of fast F^+-center emission.

Shrestha *et al* (2020b) evaluated the application of the Al_2O_3:C,Mg films in magnetic resonance-guided radiotherapy (MRgRT). Their results did not show evidence of the influence of the 0.35 T magnetic field on the OSL response, and the OSLD film dose map showed good agreement with the treatment planning system. The authors concluded that the results strongly support the use of OSLD films for 2D dosimetry of geometrical complex dose distributions.

2.2. 2D dosimetry using beryllium oxide ceramic plate

The ability of BeO ceramics to absorb the energy deposited by ionizing radiation has been known for many decades (Mandeville and Albrecht 1954). When studied as a TL dosimeter, its sensitivity to light led to the idea of investigating its application with the OSL technique (Rhyner and Miller 1970). Studies have reported promising dosimetric characteristics for the use of BeO as an OSL dosimeter (Sommer and Henniger 2006, Sommer *et al* 2007, 2008). Compared to aluminum oxide, BeO has the advantageous feature of its effective atomic number being lower (approximately 7.2 and 11.3 for Al_2O_3:C) and very close to the atomic number of soft tissue, which makes it promising for applications in radiotherapy.

In 2010, Jahn *et al* presented a 2D dosimetric system for reading a BeO OSL area detector (ceramic plates commercialized as Thermalox 995^{TM} by Materion Ceramics, Inc.). They used a point-to-point reader of the BeO area, whose main limitations were spatial resolution (impaired by the scattering of stimulation light in the detector material) and long reading time of each detector (Jahn *et al* 2010). Subsequently, this system was improved using a fiber coupled to the LED for stimulation and with the possibility of using multiple fibers for simultaneous stimulation of eight detector points (Jahn *et al* 2011). Thus, the reading time for each plate (52 $\times$ 52 mm) decreased to 2 min The authors reported a linear response to x-ray photons for doses ranging from 10 μGy to 10 Gy. They also outlined the photon energy dependence, showing that the detectors under-respond to low-energy photons (below 200 keV).

The OSL dosimetric properties of BeO are already known, and the use of the plate detector with the developed reader showed good results. The research group mentioned that the BeOmax system has been used for 2D dosimetry in different applications, such as characterization of radiation fields; dose evaluation in cell cultures, small pipes, boreholes, and tanks of reprocessing plants; dose evaluation at x-ray facilities; dose evaluation in small animal CT scans (Jahn *et al* 2013).

2.3. CaF_2 OSLD film

Yoshimura and Yukihara (2006a) reported that natural fluorite is a potential material for OSL dosimetry. Thereafter, Nakhaei *et al* (2012) presented a fiber composed of polyvinyl alcohol (PVA) and CaF_2. They synthesized CaF_2 nanoparticles using a co-precipitation method and produced PVA fibers with different amounts of CaF_2. In 2015, Nakhaei and Shahtahmassebi synthesized CaF_2:Er using a co-precipitation method and obtained PVA films through electrospinning. They concluded that the OSLD films exhibited ascending conversion luminescence and they could be used for laser and bioimaging applications in medical technology (Nakhaei and Shahtahmassebi 2015).

In 2017, Souza *et al* (2017b) reported a flexible CAF_2:Ce OSLD film in a PVC matrix. The product was produced by casting the solution, followed by evaporation of the solvent (acetone benzene). They did not evaluate the dose mapping using this film (Souza *et al* 2017). They cut the film in samples of size 0.4×0.4 cm^2 for OSL signal reading. Moreover, they established that the OSL responses on each side of the same sample of the film were similar; the maximum difference in the OSL signal of different samples of the same film was 4.5%; the dose response exhibited a linear trend of 100–700 mGy, with error bars of 10% in this preliminary study. They proposed the use of this OSLD film in patients for *in vivo* dose measurements of skin dose.

In 2018, Malthez *et al* presented a low-cost method for producing CaF_2 OSLD films consisting of natural fluorite powder in a semi-organic matrix based on acetic silicone (Malthez *et al* 2018). In 2019, Pagotto *et al* (2019) studied the energy response of CAF_2 OSLD films for personal dosimetry. Additionally, in 2019, the same group evaluated the increased detection efficiency of OSLD films by adding silver nanoparticles (Reway *et al* 2019). In 2019, Torquato *et al* demonstrated the applicability of OSLD films for 2D dose mapping in radiosurgery using the modulated volumetric therapy technique (Martins *et al* 2020a). The authors reported that the dose values along the length of the OSLD film were compatible with the values provided by the equipment plan and the values measured with the ionization chamber.

2.4. BaFBr OSLD film

Storage phosphor films are commonly used in radiology/medical imaging (von Seggern 1999, Leblans *et al* 2011), and the use of BaFBr films for dose distribution assessments is not new (Olch 2005, Li *et al* 2007).

Recently, researchers in Belgium studied the use of two different wide OSLD films experimentally produced by Agfa HealthCare for radiotherapy applications (Crijns *et al* 2017). These films are composed of two layers: polyethylene (196 μm) and an active layer with a thickness of 23 μm of BaFBr particles (5%) in a polymer binder solution (De Roover *et al* 2019). Crijns *et al* (2017) evaluated the application of one of these films, with a size of 20×18 cm^2 and an effective atomic number of 4.43 in IMRT, and De Roover (2019) tested the applicability of another film, 43×35 cm^2 and an effective atomic number of 4.55, in Extended Field Radiotherapy (EFRT).

To stimulate and read the optically stimulated signals of these films, the researchers used commercial scanners produced by Agfa HealthCare: Flying Spot CR-15-X and CR-10-X, and performed data processing in MATLAB. Using the scanner equipment, the signal was stimulated with a red laser and detected using a PMT.

De Roover *et al* (2019) established a calibration methodology for correcting the strong energy dependence of the film and confirmed its applicability in clinical dosimetry with a resolution of 0.2 mm. The dose response to 6 MV linear accelerator photon beams was linear from 0 Gy to 32 Gy (Crijns *et al* 2017).

In addition to the methodology of correction by energy dependence and evaluation of the dose response, the researchers did not evaluate other dosimetric characteristics such as signal fading. In this case, they set a standard time between irradiation and reading of 5 min for all their measurements, and they repeated the reading more than once to ensure the clearing of the OSL signal of the film.

Another research group published a study conducted with BaFBr:Eu, in which they produced detectors based on a silicone elastomer (Kim *et al* 2018), and proposed its use for 1D dosimetry *in vivo*. They produced flexible tapes with dimensions of $5 \times 100 \times 1$ mm^3 and developed a translational reading system for these tapes. They considered that the intensity of the photoluminescence (PL) signal is proportional to the density of the material; therefore, they used the PL value to correct the measured OSL signal to normalize the results to variations in tape density.

This study reports the linearity of the response with doses up to 6 Gy. The spatial resolution of the film and reader system was 1.09 mm $\pm$ 4.5%. The authors discussed two difficulties of the material that affected the results: fading of the OSL signal (they observed approximately 20% of OSL signal decay in 20 min) and long-life phosphorescence (they calculated that to reduce the uncertainty of the results, they should wait 18 min after irradiation to perform the reading of the tape). This work concludes that BaFBr:I is not a suitable material for these tapes because of these characteristics.

In Japan, Sato *et al* (2019) used transparent thermoplastic resin (Bendlay^{TM}). Instead of a film detector, they fabricated a string-shaped OSLD with BaFBr:Eu^{2+} that is bendable and reusable. A 1D OSL reader was designed using a stepper motor for sample positioning, green LEDs for signal stimulation, and a PMT for detection. The group performed x-ray and gamma-ray irradiation and obtained the OSL signal using a laboratory-built reader. They concluded that OSL string-shaped dosimeters with BaFBr:Eu^{2+} could be used for 1D dose measurements in different applications and they suggested future investigations using other OSL materials aiming to overcome signal fading.

2.5. SrS:Ce, Sm OSLD film

More than two decades ago, researchers in France proposed the use of OSLD films composed of an active layer of magnesium sulfide particles doped with cerium and samarium deposited in Kapton^R films for dose mapping in high-energy electron beams (Dusseau *et al* 1999).

In 2004, Idri *et al* used this type of film, prepared with 150 μm thickness and size 15 $\times$ 15 cm^2, to evaluate the distribution of doses in photon beam radiation fields in IMRT. The developed reader system consisted of an infrared LED for stimulation and a PMT for signal detection. The authors reported a spatial resolution of 500 μm, a linear response with dose in the range of zero to 10 Gy, and a 4.7% variation in the OSL response for different photon beams with energies ranging from 6 to 18 MeV. They concluded that it is possible to map the dose distribution in IMRT using OSLD films of SrS:Ce,Sm (Idri *et al* 2004).

The disadvantage of this type of OSLD film is the low maximum temperature to which it can be subjected so as not to damage itself and enable its reuse (Dusseau *et al* 1998).

2.6. KCl:Eu^{2+} OSLD film

Nanto *et al* (1993) irradiated europium-doped potassium chloride with a diagnostic x-ray beam and described its OSL emissions.

In 2009, Han *et al* (2009) conducted a preliminary study on the use of KCl:Eu^{2+} with the OSL technique for IMRT dosimetry. They concluded that the material had satisfactory dosimetric characteristics and they suggested future studies to develop an area detector using modern thin-film techniques aimed at reusable and high-resolution two-dimensional dosimeters for IMRT commissioning and quality assurance.

Additionally, using Monte Carlo simulation data, Zheng *et al* (2010) concluded that the thickness of the dosimeter has a direct impact on sensitivity and its overall energy response. They suggested that a KCl:Eu^{2+}-based film with a thickness of the order of a few microns could provide a reusable, quantitative, high-resolution, high-sensitivity two-dimensional dosimeter with a nearly water-equivalent dose response.

In 2014, Li *et al* reported the experimental production of KCl:Eu^{2+} films using two methods: vaporization-deposition and tape casting (Li *et al* 2014). In addition, they developed a prototype of a film reader system with a laser for stimulation and a PMT for signal detection. They performed some measurements in the laboratory, comparing the OSL response of these films with that of KCl:Eu^{2+} pellets, and obtained similar results. This initial study did not include the application of films in clinical beams. The group performed Monte Carlo simulations to estimate their energy dependence and obtained a maximum difference of 1.6% in the peripheral region (scattered photons of low energy) when they simulated a film with 20% KCl and 80% binder.

This study demonstrates the feasibility of manufacturing KCl:Eu^{2+} films in a laboratory. However, for the films to be used, given the hygroscopic nature of KCl, it is necessary to develop some form of encapsulation to protect the film from ambient humidity. In addition, the production of the film by the tape-casting method requires the development of a form of processing of KCl powder without moisture.

In summary, their results demonstrated the possibility of manufacturing and using KCl:Eu^{2+}-based films for dose mapping. Future studies should include improvements in film production methodologies and encapsulation methods (moisture protection) as well as their application in clinical beams.

2.7. NaMgF$_3$:Eu OSLD film

First, the OSL characteristics of NaMgF$_3$:Ce^{3+} were evaluated by Le Masson *et al* (2002). Thereafter, Dotzler *et al* (2007) investigated the OSL properties of Eu2+-doped NaMgF$_3$. The latter study reported a linear dose response from 3 to 100 Gy and dark fading of the OSL signal for the first 24 h.

Recently, Schuyt and Williams demonstrated the possibility of using OSLD films with NaMgF$_3$:Eu and a reader with a CCD camera for 2D dosimetry in radiotherapy (Schuyt and Williams 2019). They produced a prototype of this film in the laboratory using particles of NaMgF$_3$:Eu of sizes between 1 and 10 μm in an epoxy resin solution and cured it on a plastic layer. This film is approximately 21 $\times$ 27 mm^2 with the following thicknesses: 0.85 mm of resin layer plus detector and 200 μm of the plastic base. In addition, they proposed the use of a system for reading OSLD films with LED stimulation and detection using a CCD camera.

They compared the results of the film with those of pure NaMgF$_3$:Eu and established that the spatial resolution obtained (with the CCD camera system mounted) of the pure material was better than that of the film produced. They concluded that they should optimize the particle size and produce thinner films to improve the homogeneity and reduce scattering to ensure better spatial resolution. They evaluated the response with the dose of the material to x-ray photons of maximum energy of 40 keV, and the results indicated linearity less than 1 Gy to 100 Gy. Further studies are needed to obtain thinner and more homogeneous films.

2.8. $LiMgPO_4$ OSLD film

As several researchers are looking for detector materials that are suitable to be used with the OSL technique, $LiMgPO_4$ (LMP) has been evaluated by several researchers. Authors have reported the OSL response of LMP with different dopants (Dhabekar *et al* 2011, Gai *et al* 2013, Kulig *et al* 2016).

Sadel *et al* (2020a, 2020b) presented an OSLD film produced with silicone and $LiMgPO_4$, which has high sensitivity and a linear dose response for a wide range of doses. The film had three diameters (8, 14, and 25 mm) and it was 0.4 mm thick. They established an annealing procedure with bleaching in the Risø reader: stimulation with blue LED for 30 min at 200 °C and reported satisfactory reproducibility in repeated OSL readings (with this treatment between them).

Additionally, they evaluated the OSL response of these films using both the Risø reader and a fluorescent microscope with a highly sensitive CCD camera. They observed that the OSL signal fading reached 30% after 2 h of dark storage of the detectors. In the evaluation of the response with the dose ranging from 2 to 100 Gy, they reported a slight supralinear trend.

They also tested the applicability of the OSLD films in the clinical dosimetry of proton therapy. They used 13 OSLD films of 14 mm each in PMMA simulator blocks and irradiated them with a collimated beam (5 mm diameter) of protons (58.8 MeV). They obtained the relative dose in water at each depth and compared it with the results obtained from the Markus ionization chamber. They verified that the OSL response is 50% lower at the Bragg peak. After correction, they reconstructed the distribution of doses in water.

Recently, Sadel *et al* (2021) used a stack of 40 2D OSLD films and a specially designed eyeball phantom to reconstruct the 3D proton dose distribution after irradiation with a 58.8 MeV modulated and collimated proton beam. They aimed to verify the proton treatment plan prepared for eyeball cancer, and their results exhibited a good agreement between the reconstructed 3D OSL proton depth dose distribution and the clinical treatment plan. These results are promising, and further investigations of the relative luminescence response to protons and the dependence on proton energy are necessary.

2.9. LiF:Mg,Cu,P OSLD film

Lithium fluoride is the most commonly used material for TL dosimetry (Bilski 2002). LiF:Mg,Cu,P has also been studied as an OSLD (Bilski *et al* 2014, Sądel *et al* 2019a, 2019b).

Sadel *et al* (2020a) reported the production of silicone-based OSLD films in the laboratory using LiF:Mg,Cu, P. They justified the choice of this detector material because the effective atomic number is lower than that of aluminum oxide, and it is not toxic in the form of a powder, such as BeO.

They produced transparent and flexible films with a diameter of 8 mm and a thickness of 0.5 mm. They performed the OSL readings in a system developed by them, with stimulation by a blue LED and detection by CCD camera, and in the OSL Risø reader for comparison.

Their results demonstrated good reproducibility with the established annealing and bleaching methodology. The agreement between the results obtained from the CCD camera system and the Risø reader demonstrates that the developed reader system is satisfactory. Moreover, they presented a response with doses ranging from 1 to 100 Gy with a sublinear tendency, and the fading of the OSL signal (protected from ambient light) reached 50% in 4 h. Other dosimetric properties of the proposed films have not been reported.

This research demonstrates the possibility of producing small OSLD films based on silicone and LiF:Mg,Cu, P and the use of an image reader system with a CCD camera developed in the laboratory. The authors state that further study is needed to produce larger films with good homogeneity and image processing (corrections) should be improved to make it possible to read larger OSLD films. The films produced have not yet been tested in applications.

It should be mentioned that in the same year, Nyemann *et al* (2020) characterized the OSL emission spectra of LiF:Mg,Cu,P for different wavelength stimulation and concluded that it is a suitable material for a 3D dosimeter.

2.10. MgB_4O_7:Ce, Li OSLD film

After the successful development of an OSL laser scanning reader for aluminum oxide films (Ahmed *et al* 2017), Shrestha *et al* (2020a) studied the possibility of using MgB_4O_7:Ce,Li films to overcome the pixel bleeding limitations observed with the aluminum oxide films. Previous studies have shown promising results with the use of this material for OSL dosimetry (L. F. Souza *et al* 2017, Gustafson *et al* 2019).

The research group concluded that the fast luminescence lifetime associated with Ce^{3+} emission of approximately 31.5 ns is advantageous for 2D dosimetry in terms of laser-scanning readout when compared to the use of aluminum oxide films.

In this work, the group produced MgB_4O_7:Ce, Li powder in a laboratory, and test films (7×7 cm^2) were produced by Agfa Healthcare Inc. The group characterized the phosphorescence signal and established a 15 min pause between irradiation and readout. The reported dose response was linear up to a dose of 10 Gy.

The OSLD films were bleached and could be reused because the residual dose level was negligible relative to the typical radiotherapy dose range. However, film dose-dependent sensitization was observed, which requires further study.

The research has also reported dark fading as high as 40% in 70 h (relative to readout 30 min after irradiation) when using the OSL initial intensity measurements.

The authors indicated the potential of developing a convenient 2D dosimeter based on the OSL of MgB_4O_7:Ce, Li, and the causes of the sensitivity changes and fading should be identified for these problems to be minimized.

3. Discussion

Currently, the search for film detector materials with adequate dosimetric properties to be used with the OSL technique in measurements with different types and energies of radiation has become a major challenge in dose mapping. The two most advanced-stage studies with satisfactory applications in 2D dose mapping are based on commercial prototype detectors (Al_2O_3:C and BeO), whose production is the monopoly of Landauer, Inc. and Materion Ceramics, Inc., respectively. Notably, the use of BeO powder in a research laboratory is complicated owing to its toxicity.

Despite promising results, all the non-commercial OSLD films studied are still exploratory. The main technical reason for this could be the lack of better-suited OSL material.

We can conclude that some studied OSL materials are not suitable for dose mapping applications because of their dosimetric properties. For instance, BaFBr has long-life phosphorescence, and BaFBr, LiF:Mg,Cu,P, $LiMgPO_4$, and $NaMgF_3$:Eu exhibit high signal fading. The loss of signal over time is not necessarily an impediment to dose distribution assessment. To overcome this problem, well-established correction methodologies are required. Apart from signal fading, MgB_4O_7:Ce,Li could be a promising material for 2D dosimetry in terms of laser-scanning readout because of its fast luminescence lifetime, although there is still a need to minimize the problems owing to sensitivity changes after previous irradiations.

Regarding film manufacturing, the physical properties of the OSL material must be considered. For instance, the hygroscopic nature of KCl poses significant challenges to film production in addition to its relatively high atomic number. $NaMgF_3$:Eu, which has an appropriate atomic number and several desirable dosimetric properties, requires further study to optimize the production of films.

Regarding the film matrix, although we know that the Kapton^R film imposes a maximum temperature annealing limitation, there is little information about the characteristics of the matrices (epoxy resin, PVC, silicone elastomer, and thermoplastic resin) that have been used in laboratory-produced film studies. It is certain that matrices should be further evaluated in terms of their thermal limitations, influence on the OSL signal, and durability. For instance, the mechanical characteristics as resistance to the number of irradiation cycles and readings are not mentioned in the literature.

In fact, none of the reviewed articles evaluated the reusability of OSLD films. Detector reusability is one of the most advantageous characteristics of the OSL technique, and it is desirable to use the same OSLD film at least for one set of both calibration and measurement.

As far as the OSLD film size, few articles cited the use of larger films (50–100 cm^2). Most of these are commercial films or commercial prototype films. Many authors produced films in laboratory with a size range of 10 cm^2 or lower and most of them did not discuss the possibility or the limitation of producing smaller or larger OSLD films. The film production methodologies were not detailed in most of those manuscripts.

As for the OSL reader system, various research groups have widely assembled promising readers using different configurations: LED, laser, or halogen lamp for stimulation and PMT, CCD camera, or CMOS camera for detection, in addition to mechanical setups and software. Moreover, versatility is expected because the most advantageous characteristic of OSL over the TL technique is the easier readout (optical readout). One negative aspect to be considered is the high cost of CCD cameras, which has not been previously mentioned. Furthermore, the reading conditions were adjusted according to the characteristics of the detector material. The optimistic result from the measurement data is that it has been shown that correction factors and algorithms can overcome some material dosimetric property limitations. However, the search for a better-suited OSL material continues.

The relative simplicity of optical readout and relatively compact OSL readers make it possible to hold 2D OSL systems in the irradiation site. It is particularly interesting for radiation dosimetry quality assurance measurements in clinics and hospitals. Consequently, dose distributions would be immediately verified. In addition, considering the relatively low cost and the possibility of stimulation of only a very small portion of the OSL signal, the OSLD films could be stored for record of the measurements (provided the material does not present OSL signal fading or correction factors are well established).

Although some research groups have preliminarily only evaluated OSLD films in the laboratory, various studies have successfully tested the use of OSLD films (or ceramic plates) for dose mapping in different applications. The primary application mentioned is quality assurance in radiation dosimetry, such as IMRT, EFRT, LINAC radiosurgery, and proton therapy dose-distribution verification. Especially the prototype OSLD films of Al_2O_3:C and Al_2O_3:C, Mg which were tested for MRgRT application with successful results as the measurements were not affected by the magnetic field.

Other applications in which OSLD films could be useful are dose evaluations in space dosimetry, boreholes, small geometries in general, tanks of reprocessing plants, general x-ray facilities, mammography, interventional fluoroscopy, CT, animal CT, dental radiography, CyberKnife radiosurgery, other small fields, postal audits in general, and others (Yukihara and McKeever 2011, Jahn *et al* 2013).

Small field dosimetry and real-time dosimetry using optical fibers are the two main applications that deserve deeper studies using OSLD films.

As radiation therapy technologies are in continuous development, high resolution dosimetry is needed and the use of OSLD films for small field dosimetry is promising and could be the solution to current limitations such as difficulty in positioning a detector in the radiation field, low resolution on point detector arrays, volume averaging effect on larger detectors, the response of radiochromic films dependent on dose rate, and others (Kron *et al* 2016, Parwaie *et al* 2018).

Real-time dosimetry using optical fibers is already accomplished using OSL point detectors (Edmund *et al* 2006, Gaza and McKeever 2006, Klein and McKeever 2008). The use of OSLD films and the development of 2D reader systems could optimize these types of measurements. It is worthy to emphasize that various OSLD films previously mentioned could be tested, including the ones made with OSL materials that present high OSL signal fading as it should not be a problem for real-time measurements. For this type of measurement, however, it is important that the OSL signal of the material decays fast (fast trap emptying) and that the luminescence lifetime is very short.

4. Conclusion

Three important observations were made in this review. First, different OSL materials have been evaluated for use in 1D and 2D dose distribution assessments, and although there are a few promising materials, there is no consensus on the best OSL material for each application, for instance, for IMRT dose mapping. Second, different matrix materials and methods have been used for film production, independent of commercial prototypes or laboratory fabrication. Third, various options for OSL reader assembly are being tested for a 2D OSLD film readout. Therefore, we conclude that publications in the international literature prove the feasibility of using OSLD films for 1D and 2D dose mapping although the choice of the most suitable OSL material is challenging and requires further studies. Nevertheless, 2D systems with OSLD films could become the next solution for dose distribution mapping with high resolution including in small field applications.

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