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Effect of Magnetic Field Strength on Plastic Scintillation Detector Response

F. Therriault-Proulx, Z. Wen, G. Ibbott, and S. Beddar*

Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, 1515 Holcombe Blvd., Unit 1420, Houston, TX, USA

Abstract

Purpose—To characterize the response of plastic scintillation detectors (PSDs) to high-energy photon radiation as a function of magnetic field strength.

Materials and Methods—PSDs were placed inside a plastic phantom held at the center point between 2 magnets and irradiated using a 6-MV photon beam from a linear accelerator. The magnetic field was varied from 0 T to 1.5 T by 0.3-T increments. The light emission and stem-effect-corrected response as a function of magnetic field strength were obtained for both a commercial PSD (Exradin W1, Standard Imaging) and an in-house hyperspectral PSD. Spectral signatures were obtained for the in-house PSD, and light emission from a bare fiber was also measured.

Results—Light emission increased as magnetic field strength increased for all detectors tested. The tested PSDs exhibited an increase in light intensity of 10% to 20%, mostly owing to the increase in Cerenkov light produced within and transmitted along the optical fiber. When corrected for stem effects, the increase in PSD response went down to 2.4% for both detectors. This most likely represents the change in the inherent dose deposition within the phantom.

Conclusion—PSDs with a suitable stem-effect removal approach were less dependent on magnetic field strength and had better water equivalence than did ion chambers tested in previous studies. PSDs therefore show great promise for use in both quality assurance and *in-vivo* dosimetry applications in a magnetic field environment.

Keywords

Scintillation; PSD; dosimetry; Magnetic-field; MR-Linac; Cerenkov effect

1. Introduction

The use of magnetic resonance imaging during radiation therapy is revolutionary, promising to improve the precision and personalization of treatment delivery. However, the presence of

*Corresponding author: Sam Beddar, Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, 1515 Holcombe Blvd., Unit 1420, Houston, TX 77030, USA, abeddar@mdanderson.org.

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a magnetic field for imaging can reduce the accuracy of existing detectors used for radiation dosimetry and quality assurance measurements (Raaijmakers et al., 2005; Raaymakers et al., 2004). Researchers, therefore, are increasingly interested in studying the behavior of existing radiation measurement devices in the presence of magnetic fields and in developing new ones whose response is less strongly affected by magnetic fields (Agnew et al., 2017; Hackett et al., 2016; O'Brien et al., 2016; Reynolds et al., 2013, 2014). Because they are composed of nonmagnetic materials, plastic scintillation detectors (PSDs) are promising for such applications. PSDs have several advantages over other types of detectors, including their water equivalence, small size, and fast response (Beddar et al., 1992a, 1992b, 1992c). PSDs have also attracted great interest for small-field quality assurance and *in-vivo* dosimetry applications (Kamio and Bouchard, 2014; Klein et al., 2010; Mijnheer et al., 2013; Tanderup et al., 2013). However, Stefanowicz and colleagues (2013) reported an increase in light intensity of up to 7% when PSDs were exposed to a magnetic field ranging between 0 and 1 T; the underlying causes for this effect were not well understood.

The purpose of the present study was to measure the magnetic field strength dependence of the light response of PSDs. We analyzed the light response from both a commercial PSD and an in-house hyperspectral PSD by measuring changes in the intensity and spectral composition of the emitted light in the presence of magnetic fields of varying strengths. Our goal was to obtain a better physical understanding of the effects of magnetic fields on PSD response.

2. Materials and Methods

The responses from a commercial PSD, an in-house PSD, and a bare fiber were obtained for different magnetic field strengths. An insert was used to hold the PSD at the center of a 10 cm × 10 cm × 20-cm acrylic phantom (Fig. 1a). The hole containing the insert was filled with water to prevent the hard-to-predict effects of air gaps in the presence of a magnetic field (Hackett et al., 2016). The phantom was held firmly by its sides at the center point between the 2 magnets. The current applied to the magnets was varied to create magnetic fields ranging from 0 T to 1.5 T in 0.3-T increments. As depicted in Fig. 1b, the magnets and detector were placed at the far left end of the clinical vault, with the detector 3.7 m from the radiation source. The field size at the PSD was 3 cm × 10 cm. The detector was irradiated with a 6-MV photon beam from an Elekta Versa HD linear accelerator (Elekta, Stockholm, Sweden), with the gantry positioned at 90 degrees.

The commercial detection system was composed of an Exradin W1 scintillator (Standard Imaging, Middleton, Wisconsin, USA) connected to a 2-channel Supermax electrometer (Standard Imaging). The readings from each channel were corrected for stem effects according to procedures detailed by Guillot et al. (2011). The in-house PSD system was composed of a 3-mm-long BCF-60 scintillating fiber coupled to a 15-m-long optical fiber (GH-4001, Mitsubishi, Tokyo, Japan) connected to a spectrometry system consisting of a Shamrock spectrograph (Andor, Belfast, Ireland) and a charge-coupled device camera (DU-420, Andor). The in-house system allowed us to ascertain the spectral response of the incoming light, kept the photodetection system outside of the room, and enabled us to use the hyperspectral approach for stem-effect removal, following the method previously

described by Therriault-Proulx et al. (2013). The same spectrometry system used with the in-house PSD was also used with a bare fiber to study the stem effect. The PSDs' responses as a function of magnetic field strength incorporated measurements of signal intensity, spectral signature, and stem-effect-corrected signal.

3. Results

3.1. Light intensity

The light intensity as a function of magnetic field strength for both channels of the commercial (W1) PSD, the in-house PSD, and the bare fiber is shown in Fig. 2. Responses were normalized to the response without a magnetic field ($B = 0$ T). In all cases, light intensity increased as the magnetic field strength increased; this effect was particularly noticeable for the bare fiber.

3.2. Spectral study

Figure 3 shows the measured spectra with a 1.5-T magnetic field and without a magnetic field ($B = 0$ T), normalized to the area under the curve. From the shapes of the spectra, it can be inferred that the different components of the signal were affected differently by the magnetic field. The spectral signatures of the components of the signal (scintillation, Cerenkov stem effect, and fluorescence stem effect) were also obtained and are shown in Fig. 3. These signatures were used to implement the hyperspectral approach for stem effect correction, which accounted for both Cerenkov and fluorescence effects.

3.3. Stem-effect-corrected measurements

Figure 4 shows the stem-effect corrected response of the commercial and in-house PSDs, determined using the 2-channel and hyperspectral approaches, respectively. The behavior of the detectors in response to the magnetic field strength was similar. Most of the increase in light intensity shown in Fig. 2 was corrected for, with a remaining difference of about $(2.4\% \pm 0.3\%)$ for the commercial PSD and $(2.4\% \pm 0.1\%)$ for the in-house PSD. Possible causes for this difference are discussed in Section 4.

4. Discussion

All detectors exhibited an increase in light intensity along with increasing magnetic field strength. This increase was especially pronounced for the bare fiber, in which the light intensity increased by 79% from 0 T to 1.5 T. Moreover, channel 1 and channel 2 in the commercial PSD system exhibited different changes in light intensity with magnetic field strength (10% for channel 1 vs. 20% for channel 2 at 1.5 T). Taken together, these data lead us to conclude that the Cerenkov effect was the main cause of this variation. Indeed, because Cerenkov light is emitted at a specific angle relative to the direction of the electron depositing the dose (Beddar et al., 1992c), the effect of a magnetic field on an electron's path may markedly affect the amount of light coupled into the optical fiber. This is not true for the scintillation light or the stem effect light that comes from fluorescence because these forms of light are emitted isotropically. Application of the hyperspectral approach to the response of the in-house detector confirmed that the Cerenkov effect was the main

contributor to the difference in this detector's response with and without the magnetic field. As shown in Fig. 3, the shapes of the spectra obtained with and without the magnetic field were different, confirming that the components of the PSD's response made different relative contributions to the total signal depending on the presence of the magnetic field. As shown in Fig. 4, the stem-effect-corrected response was similar for the commercial and in-house detectors, leading to the conclusion that variation in the fluorescence component of the stem-effect light was negligible in comparison to variation in the Cerenkov light component. The latter is supported by the fact that fluorescence is emitted isotropically and represents in magnitude about 3.5% of the stem-effect signal in such irradiation conditions (Therriault-Proulx et al. 2013).

The use of stem-effect removal approaches had a remarkable impact in correcting the dependence of the PSDs' light emission responses on magnetic field strength. The measured increase in light intensity in the presence of a magnetic field was 10% to 20% (depending on the signal) but only 2.4% after stem-effect removal. Our observed increases in light intensity with magnetic field strength were higher than those reported by Stefanowicz et al. (2013), which ranged up to 7% for a magnetic field strength of 1 T. However, it is important to note that the latter study used band-pass and notch filters around the scintillator's peak emission wavelength, which acted as a partial stem-effect removal technique. In light of our results, we recommend using an approach allowing for complete stem-effect removal when PSDs are employed within a magnetic field.

The remaining 2.4% we observed could possibly be explained by factors other than the response from the PSD. Even though we took precautions to avoid them, it is possible that small air gaps between the phantom and the PSD still existed. Nonetheless, it is unlikely that air gaps can account for the entire 2.4% variation, as changes of only 0.7% to 1.2% were reported by Hackett et al. (2016) for an ionization chamber exposed to a magnetic field. It is more likely that this difference is attributable to the inherent difference in dose deposition to the detector volume as a function of the magnetic field strength. Indeed, because a magnetic field deflects an electron towards a helicoidal trajectory, it can be expected that the deposited dose inside detectors subject to magnetic fields would differ from the dose without a magnetic field. Good agreement between dose measurements performed with ionization chambers and Monte Carlo calculations of the deposited dose inside the chambers was previously reported by Reynolds et al. (2013, 2014). However, because of the ionization chamber's composition (i.e., air), the differences in measured doses in the presence of a magnetic field were on the order of 8% to 11% for a 1.5-T field, depending on the detector's orientation (Meijsing et al., 2009). Because the detectors used in the present study were made of plastic, it is not surprising that the response changes in the presence of a magnetic field would be smaller after correction for stem effects. Furthermore, O'Brien et al. (2016) reported that the dose in water at $d_{\max}$ calculated using Monte Carlo simulations for a 6-MV photon beam in the presence of a 1.5-T magnetic field was 2.2% higher than the dose without a field, which is in line with our observations. Simulations of our specific irradiation setup would be required to obtain more conclusive evidence, but it seems likely that the known water-equivalence of PSDs still holds true under the effect of a magnetic field.

5. Conclusion

Our results demonstrated that PSDs show great promise for dosimetry applications in the presence of magnetic fields. The Cerenkov effect was shown to be the main component of the changes in PSD response with magnetic field strength. When the Cerenkov effect is corrected for, the difference between the dose with and without the presence of a magnetic field was noticeably smaller than it is for ionization chambers. Moreover, this difference most likely reflects the actual difference in deposited dose within the phantom, not differences in PSD response or interactions within the PSD. Both detectors tested in this study would therefore be suitable for accurate measurements of deposited dose in a magnetic field environment and could be implemented as part of quality assurance and *in-vivo* dosimetry applications for magnetic resonance linacs and other treatment modalities employing magnetic resonance imaging.

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Highlights

- Cerenkov effect is responsible for the dependence of PSD response to magnetic fields.
- A proper stem-effect removal approach corrects for this dependence.
- PSDs are less dependent on magnetic field strength than ion chambers.
- PSDs are promising for dosimetry applications in a magnetic field environment.

Fig. 1.

(a) Plastic scintillation detector held at the center of an acrylic phantom between magnets. The magnetic field strength was varied from 0 T to 1.5 T by selecting the current applied to the coils. (b) Position of the plastic scintillation detector inside the clinical vault. The detector was placed 3.7 m from the radiation source.

Fig. 2. Light intensity as a function of magnetic field strength. Responses were normalized to those obtained during magnetic-field-free ($B = 0$ T) irradiations.

Fig. 3. Optical spectrum response of the in-house PSD with ($B = 1.5$ T) and without ($B = 0$ T) a magnetic field. The scintillation and stem effect signatures from both Cerenkov and fluorescence are also shown.

Fig. 4. Stem-effect-corrected responses as a function of magnetic field strength for the commercial (W1) PSD and the in-house PSD. The 2-channel and hyperspectral stem-effect removal approaches were used, respectively. Error bars represent one standard deviation from repeated measurements.