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RESEARCH ARTICLE

MEDICAL PHYSICS

Dosimetry in MRgPT: Impact of magnetic fields on TLD dose response during proton irradiation

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Abstract

Background: Proton beam therapy, when integrated with MRI guidance, presents complex dosimetric challenges due to interactions with magnetic fields. Prior research has emphasized the nuanced impact of magnetic fields on dosimetry. For thermoluminescent dosimeters (TLDs) the electron-return effect, alongside small air cavities surrounding the pellets, can lead to nonuniform dose distributions. Future MR-guided proton therapy will require reliable methods for end-to-end tests and dosimetric audits, which so far are often performed using TLDs equipped with phantoms. This implicates the necessity of accounting for these interactions.

Purpose: This study investigates the influence of magnetic fields on TLDs at two proton energies, using magnetic field strengths of 0, 0.25, and 1 T, aiming to clarify their impact on dose measurement accuracy.

Methods: The study was conducted at a synchrotron-based ion beam therapy beam line, enhanced by a resistive dipole magnet for creating magnetic fields up to 1 T to simulate MR-guided proton therapy. Individual correction factors were applied for TLD measurements. The impact of air gaps on the TLD signal was evaluated using three dedicated TLD holders with air gaps of 0.1, 0.25, and 0.5 mm surrounding the TLD pellets using the highest available proton energy of 252.7 MeV. Additionally, the influence of the magnetic field strength on the TLD response was evaluated for two proton energies of 97.4 MeV and 252.7 MeV.

Results: The study found no statistically significant variation in TLD dose response attributable to changes in the air gap or the presence of magnetic fields. A power analysis indicated an upper limit on a potential change in dose-response as small as 1.5%.

Conclusions: The findings suggested that the impact of air gap variations and magnetic field strengths on the TLD response was below the detection threshold of TLD sensitivity. This emphasizes the suitability of TLDs for dose measurement in MR-guided proton therapy, indicating that additional correction factors may not be necessary despite the influence of magnetic fields.

KEYWORDS
dosimetry in magnetic fields, proton therapy, TLD

1 INTRODUCTION

Proton therapy is a highly conformal treatment modality but sensitive to range uncertainties due to anatomic variations, requiring considerable treatment margins. To further increase treatment efficacy, high-quality image modalities will be beneficial, enabling detection of such variations, and allowing a reduction of treatment margins. The limited soft-tissue contrast of x-ray-based methods as well as the imaging dose makes this imaging modality less appealing compared to magnetic resonance (MR) imaging. Consequently, the use of MR is steadily increasing. A combination of photon therapy with on-treatment bed MR imaging, the MR-linac is already in clinical routine. Proton therapy would benefit even more from this possibility.[1] Prototype systems, combining on-bed MR with proton therapy are already under development. In-vitro studies so far did not identify any magnetic field-dependent change in biological effectiveness.[2]

The introduction of strong magnetic fields during irradiation and the subsequent effects on charged particles pose additional challenges to dosimetry. For the MR-linac considerable magnetic field dependencies of detectors have been shown.[3,4]

Active detectors, especially ionization chambers play an important role during commissioning as well as quality assurance for any proton therapy center. For such active detectors changes in response in the presence of a magnetic field were found to be smaller in proton therapy compared to MR-guided photon therapy, but still significant.[5,6] Another option are solid-state detectors, such as a MicroDiamond detector. Interestingly, small effects have been reported,[5] although in an orientation that is typically not used clinically.

In passive detectors, such as Gafchromic EBT-3 films, current studies have not identified any significant impact of magnetic fields on the dose-response during proton irradiation.[7]

Due to the presence of a magnetic field, the so-called electron-return effect arises, which was observed for photon as well as proton irradiation.[8–10] In the presence of a magnetic field, secondary electrons may deviate from their initial trajectory, leading to the deposition of dose in regions not anticipated by the primary dose distribution. This effect becomes particularly pronounced in the presence of density changes, such as air cavities, which are often encountered when using passive dosimeters. The comparatively lower energies of the secondary electron spectra in proton therapy suggest that air cavity-related dose changes are of critical concern and therefore should be reduced.

TLDs are commonly employed in radiation therapy for in-vivo measurements to monitor the actual dose received by patients and out-of-field dose measurements,[11] preclinical research[12] as well as assessing occupational exposure in personnel.[13] A further prominent use case is for end-to-end tests as well as dosimetry audits. Such audits are often required for clinical trial participation. The Imaging and Radiation Oncology Core Quality Assurance Center at Houston (IROC Houston) funded by the National Cancer Institute to audit radiotherapy sites uses various phantoms equipped with TLDs to audit proton therapy centers.[14,15] Although TLDs are widely used in dosimetry for photons,[16] their application in particle beams is less common.[17] Multiple groups have investigated the suitability of TLDs for photon dosimetry in magnetic fields, that is, MR-linacs, with mixed results. Copty et al.[18] investigated the impact of magnetic fields on the performance of personal dosimeters during photon irradiation. Their findings revealed a significant deviation in the response of lithium borate copper-doped (LiBo:Cu) TLDs dosimeters when exposed to a magnetic field strength of 0.2 T. One group using powder-based TLDs reported changes of 2.3% for a parallel magnetic field orientation.[19] A possible explanation for this may lie in the presence of an air gap within the TLDs vessel. In contrast, other research groups employing fully filled vessels reported no such effect.[3,18,20] Although the majority of groups report no changes in dose-response in the presence of magnetic fields for photons, some TLDs materials such as TLD 600 or experimental setups showed noticeable effects, especially in the low magnetic field range of 0.2 T.[3,4]

Our investigation is the first study of TLDs under proton beam irradiation in the presence of magnetic fields. It specifically aims to determine whether magnetic fields exert any effect on the dosimetric response of TLDs in the context of proton beam therapy. Furthermore, it assesses the influence of air gaps between the TLDs and the holder material on measurement accuracy and reliability in varying magnetic field strengths, an important influence factor for dosimetry audits and end-to-end tests.

2 MATERIAL AND METHODS

2.1 Experimental room

The research room at the MedAustron facility is equipped with a horizontal beam line and a clinical nozzle, allowing treatment with field sizes up to 20 cm × 20 cm with protons or carbon ions.[21,22] In addition, a resistive dipole magnet (Danfysik, Taastrup, Denmark) allows the creation of magnetic fields up to 1 T, with a pole diameter of 25 cm and an effective pole gap of 13.5 cm. The magnet can be positioned in front of the nozzle such that the magnetic field isocenter and the isocenter of the beam line are aligned. More details on the beamline and the magnet assembly can be found in previously published work.[5,7,23]

2.2 | TLD processing

A total of 180 TLD-100 thermoluminescent dosimeters from TLD Poland (Krakow, Poland), composed of LiF:MgTi and featuring a natural ^{6}Li/^{7}Li isotopic abundance, were employed in the study. The TLD disks had a diameter of 4.5 mm and a thickness of 0.9 mm. The TLDs were organized into sets of 48 to align with the capacity of the reader, which can process that number of TLD chips simultaneously. Prior to irradiation, the TLDs were annealed at 400 °C for 1 h followed by 4 h at 100 °C. The readout was performed in a Model DA-20 TL/OSL Reader (Risø, DTU Nutech, Denmark) employing a heating rate of 5 °C per second with a final temperature of 400 °C. In total 400 data-points were sampled from the glow-curve. A continuous nitrogen flow was used to reduce chemiluminescence and spurious signals not related to the irradiation.[24] The light signal of the highest peak plus the surrounding 20 bins was used for dose evaluation employing an in-house developed Python script.

Due to batch heterogeneity, each TLD was corrected for its response by applying individual correction factors (ICFs).[25,26] The ICF is the ratio of the specific response of a single TLD to the average light signal of a set. The ICFs were determined using the ^{90}Sr/^{90}Y beta source installed in the TLD reader.[27] All TLDs were exposed to this beta source for 300 s, after the annealing process. This procedure was repeated three times and the averaged ICFs henceforth were used for all dose measurements outlined in this manuscript. The usage of ICFs reduced the measurement variability of the TLDs, as indicated by a decrease in the three-sigma value from 12.4% to 4.0.%.

2.3 | Irradiation setup

TLD holders were designed for insertion into a 2 cm thick polymethyl methacrylate (PMMA) slab of 12 cm × 30 cm. The TLDs were positioned 1 cm from the surface of the assembly, behind a 1 cm PMMA plate. Additionally, 15 cm of PMMA was placed downstream from the TLD holder. This PMMA assembly was inserted inside the magnet in such a way that the surface of the TLD holder was located 10.5 cm in front of the isocenter. The assembly was placed at the periphery of the magnetic field to minimize the influence of magnetic field effects on the trajectories of the particles, while still being in a homogeneous magnetic field environment. A sketch of the experimental setup can be seen in Figure 1.

Monoenergetic 10 cm × 10 cm fields with a hexagonal spot spacing of 2 mm, resulting in 2500 spots, were used for irradiation. Proton beams of 252.7 MeV or 97.4 MeV resulting in a dose of 1.8 Gy at the position of the TLDs and magnetic fields of 0, 0.25, and 1 T were applied. For the 252.7 MeV and 97.4 MeV proton beams, the number of particles per spot was 1.03×10^{8} and 5.27×10^{7}, respectively. The full width half maximum (FWHM) was 7.1 mm and 14.2 mm for the 252.7 MeV and 97.4 MeV proton beam, respectively. This resulted in a 2D homogeneity of 2.5% to 2.0% for 252.7 MeV and 97.4 MeV, respectively.

The dose was verified using a ROOS electron chamber (PTW, Freiburg, Germany), cross-calibrated for proton beams.[28] The chamber was similarly positioned in PMMA and at the same effective depth of 1 cm as the TLD. Measurements were performed after preirradiation and leakage-current correction (zeroing) of the detector. Readings were corrected by temperature and pressure as recommended in the IAEA TRS 398 code of practice.[29] The dose to the point of interest in the homogeneous phantom was not affected by the magnetic field.

2.3.1 | Influence of air gaps

To explore systematically the influence of air gaps between the detector and phantom material, three unique TLD holders were used. The holders with dimensions of 8 cm × 8 cm × 2 cm were fabricated with varying air gaps using a CNC milling machine. Each holder featured a hexagonal grid arrangement, maintaining an 8 mm spacing from the center of one TLD to another able to hold 67 TLD pellets (cf. Figure 2). The TLDs were accommodated in holes designed to match their size with additional space for air gaps. The specified air gaps were 0.1, 0.25, and 0.5 mm, leading to hole diameters of 4.7, 5.0, and 5.5mm, respectively.

The highest available proton energy of 252.7 MeV was employed. We expected the largest effects for the highest secondary electron energies and ranges, which seemed to play a considerable role for ionization detectors suggesting a larger impact due to the electron return effect.[8,30]

For each of the TLD holders, measurements were performed without a magnetic field and with a magnetic field of 0.25 T, as for other detectors this magnetic field strength was shown to produce the highest effects.[5,30] In each setting, five TLDs were irradiated. To account for response uncertainties caused by the setup, the irradiations were repeated three times, resulting in a total of 15 TLDs for each airgap and magnetic field strength."

2.3.2 | Influence of magnetic field strength

To investigate how the magnetic field strength might affect the dose-response of TLDs, two initial proton energies (i.e., 97.4 MeV and 252.7 MeV) were applied combined with three distinct settings for the magnetic field strength (i.e., 0, 0.25, and 1 T). For the 252 MeV energy, a total of 60 TLDs were irradiated for each magnetic field strength, divided into sets of five TLDs. In contrast, for the 97 MeV energy, 18 TLDs per magnetic

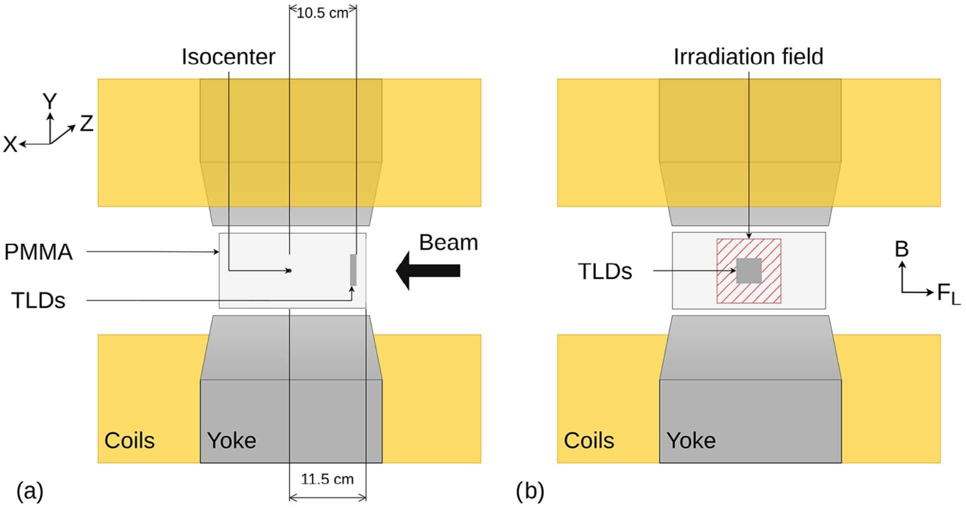

FIGURE 1 Longitudinal (a) and lateral (b) sketch of the experimental setup. The magnetic field isocenter and the room isocenter coincide in the marked position.

field strength were irradiated, and grouped into sets of six TLDs.

A magnetic field correction factor $k_{B,M,Q}$ as described in literature[5] was calculated to describe any potential change in detector response due to the ambient magnetic field. (Equation 1):

$$k_{B,M,Q}(E) = \frac{M_Q}{M_Q^B} \tag{1}$$

where M_Q^B relates to the detector reading with and M_Q without applied magnetic field B.

2.4 | Data analysis

Data preprocessing and statistical analyses were conducted using Python 3.9, utilizing libraries including `NumPy`, `pandas`, `SciPy`, and the statistics module. Median and interquartile range (IQR) (25th and 75th percentile), as well as the mean and standard deviation of the $k_{B,M,Q}$ values were reported. A Mann–Whitney U test was employed to test statistically significant differences by applying a significance level of $p < 0.05$. Furthermore, a power analysis was performed to evaluate the sensitivity of the experimental setup to detect differences in dose measurements caused by a variation of the air gap or the magnetic field strength, assuming a significance level of 0.05.

3 | RESULTS

3.1 | Effect of air gaps

The median and mean values of the TLD response are summarized in Table 1, where the data was normalized to the median response without a magnetic field. The largest change in response of 1.5% was found for the smallest air gap of 0.1 mm.

The Mann–Whitney U tests indicated no statistically significant variations in the TLD responses when comparing different air gaps for magnetic field strengths of 0 and 0.25 T.

Employing a sigma of 3% (cf. Table 1) the power analysis indicated that our method is capable of detecting a minimum effect size of 2.5% attributable to the air gap with a likelihood (power) of 95%.

3.2 | Effect of magnetic field

Table 2 summarizes the TLDs response for three different magnetic field strengths, also including the p-values from the Mann–Whitney U tests. No significant difference was observed in the presence of a magnetic field. The statistical tests compared the data points acquired at 0.25 T and 1 T to the response without any magnetic field, separately for each energy. Figure 3 shows a boxplot of the TLDs response for each field strength and proton beam energy.

The power analysis concerning the effects of varying magnetic field strengths revealed that effects as small as 1.5% could be detected with over 99% power for a proton energy of 252.7 MeV. For the 97.4 MeV proton energy, the power analysis yielded less favorable results, attributed to the increased sigma (see Table 2), and reduced sample size. Consequently, effects of 5% could be detected with a confidence level of 95%.

4 | DISCUSSION

Three unique TLD holders were investigated to analyze the potential impact of air gaps between the detector and phantom material. This aspect is crucial in TLDs

TABLE 1 Comparison of the TLD response as $k_{B,M,Q}$ at two magnetic field strengths (i.e., 0 T and 0.25 T) for three different air gaps in the TLD holder.

Air gap (mm)	Mag. field (T)	Median $k_{B,M,Q}$ (IQR)	Mean $k_{B,M,Q}$ (SD)	p-Value
0.10	0.0	1.000 (0.997–1.022)	1.006 (±0.018)	0.19
	0.25	1.015 (0.996–1.035)	1.015 (±0.023)	
0.25	0.0	1.000 (0.982–1.019)	0.997 (±0.030)	0.29
	0.25	1.008 (0.996–1.020)	1.011 (±0.024)	
0.50	0.0	1.000 (0.973–1.014)	0.995 (±0.022)	0.82
	0.25	0.998 (0.982–1.014)	0.998 (±0.024)	

Note: The proton beam energy was 252.7 MeV, using 15 samples per setting.
Abbreviations: IQR, interquartile range; TDL, thermoluminescent dosimeter.

TABLE 2 Influence of the magnetic field strength on TLD response as $k_{B,M,Q}$ for two energies (i.e., 97.4 MeV and 252.7 MeV).

Energy (MeV)	Mag. field (T)	Median $k_{B,M,Q}$ (IQR)	Mean $k_{B,M,Q}$ (SD)	p-Value
97.4	0.0	1.000 (0.948–1.006)	0.970 (±0.061)	—
	0.25	0.983 (0.947–0.999)	0.974 (±0.036)	0.51
	1.00	0.989 (0.928–0.998)	0.966 (±0.045)	0.26
252.7	0.0	1.000 (0.984–1.019)	0.999 (±0.024)	—
	0.25	1.009 (0.989–1.024)	1.008 (±0.024)	0.17
	1.00	1.002 (0.987–1.020)	1.004 (±0.027)	0.43

Note: The Mann–Whitney *U* test was performed for each energy to the response without a magnetic field, without significant differences.
Abbreviations: IQR, interquartile range; TDL, thermoluminescent dosimeter.

experiments, as the sensitive TLD material precludes compressing them into tight holders to minimize the spacing, due to the risk of causing damage. The statistical evaluation indicated that the dose-response effects of the TLDs, caused by the air gap between detector and phantom material are less than 2.5%. This underscores the effectiveness of our experimental design in identifying even subtle effects of the air gap on dose measurement accuracy with TLDs. Consequently, in MR-guided proton beam therapy, the influence of air gaps in phantom geometries—such as those between phantom material and detectors, attributed to the electron return effect[8]—falls below the detection sensitivity of passive detectors such as TLDs. This could greatly facilitate further phantom designs for end-to-end tests and dosimetric audits. In addition, the data indicates that other passive detectors, such as Gafchromic films would similarly not be affected by air-gaps.

Results showed no statistically significant differences in the dose-response of the TLDs without and with the presence of a magnetic field. With a confidence level of 99% potential effects of the magnetic field of 1.5% would have been detected for proton irradiations with 252.7 MeV. Thus, TLDs are a robust dosimetric tool for MR-guided proton therapy.

Accurate dosimetry is a precursor for MR-guided proton therapy. Determining potential effects due to the presence of a magnetic field, their understanding as well as a potential mitigation are currently being tackled by multiple groups.[6,30–32] For active detectors, besides experimental characterization also in-depth in-silico modeling is an important aspect.[31,33] Investigations might well result in the development of less magnetic field-sensitive detectors. For passive detectors, development might focus on MR-readable 3D detector systems such as polymer gels.

TLDs were positioned in the entrance region of the Bragg peak. The chosen measurement depth of 1 cm ensured a low dose gradient region, reducing the influence of positioning errors as well as being in a low linear energy transfer (LET) region. In addition, it allowed us to investigate a potential magnetic field dependency in a monoenergetic, homogeneous LET region as opposed to the mixed-energy field of a spread-out Bragg peak. Despite the frequent use of mixed fields in clinical practice, accurately distinguishing observed effects would present a challenge due to the presence of multiple confounding factors, including LET quenching. Utilizing two proton energies with a wide separation enabled the coverage of a broad spectrum of proton energies commonly used in clinical routine. LET effects were not a focus of this investigation and consequently LET quenching was not investigated.

Potential dose rate effects on the TLD response in combination with the presence of magnetic fields were not investigated in this study, due to limited possibilities to alter the dose rate in our facility. Recent literature

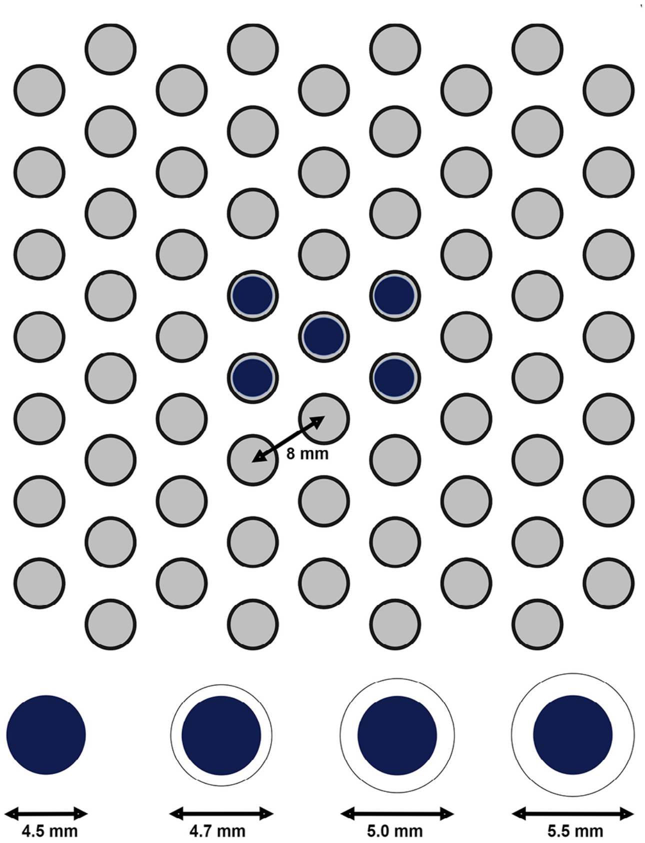

FIGURE 2 Sketch of the TLD holder. Gray circles illustrate potential TLD inserts and blue filled circles show the position of the irradiated TLDs. The distance between two TLD inserts is 8 mm from TLD center to TLD center. Three versions were constructed with varying air gaps around the TLD of 0.1, 0.25, and 0.5 mm. TDL, thermoluminescent dosimeter.

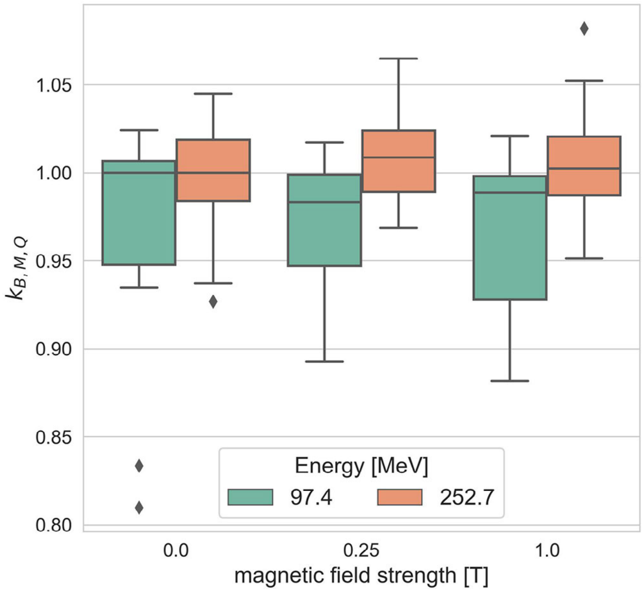

FIGURE 3 Boxplot of normalized response of TLDs for three different magnetic field strengths for two proton beam energies. The Mann–Whitney *U* test comparing data points without a magnetic field to data points with a magnetic field at identical energy showed no significant difference. TLDs, thermoluminescent dosimeters.

suggests a dose rate dependency of TLD-100 at very low doses,[34,35] which might be further investigated in the context of MR-guided proton therapy.

The quantity of data points obtained for the two energies differed considerably, with 60 for one and 18 for the other at each magnet setting. This discrepancy arose from restricted access to the proton beam, which necessitated prioritizing beam time for investigating anticipated effects at higher proton beam energies.[5,30] Furthermore, for the 97.4 MeV proton beam, two data points recorded at 0 T exhibited a low response (cf. Figure 3). Despite their deviation, these values fell within the 3-sigma range, rendering their exclusion as outliers unjustifiable. The disparity in sample size across the two proton beam energies and the corresponding variation in standard deviation, also greatly affected the power analysis, resulting in a higher effect size for the 97.4 MeV beam.

There are conflicting results concerning TLD response in magnetic fields reported in the literature. Several other studies investigating TLD response in magnetic fields for photons did not observe effects. Most notably, if effects were observed they were located in the low field region of about 0.2 T with widely varying results.[3,4,18–20] Effects observed so far for photons of various energy ranges might be correlated to secondary effects such as the change in particle trajectories of secondary electrons. This seems to be further supported by earlier work on Gafchromic EBT3 films[7,8] and would agree with our results for protons.

Incorporating our observations from proton irradiation studies it appears that the magnetic field strength does not influence the mechanism causing the dose-response with TLDs.

5 | CONCLUSION

In conclusion, our analysis indicates that the uncertainty of our TLD measurements surpasses any potential effects induced by magnetic fields up to 1 T during proton irradiation. Furthermore, there is no indication that variances in the air gap of 0.1 mm to 0.5 mm between the TLD and the surrounding phantom material influence dosimetric proton measurements with TLDs. Combined with Gafchromic film dosimetry, TLDs seem suitable candidates for end-to-end tests and dosimetry audits in MR-guided proton therapy.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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