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Title:

Technical Note: Experimental characterization of the dose deposition in parallel MRI-linacs at various magnetic field strengths

Running Title:

Parallel MRI-Linac dose deposition at 1 and 1.5 T

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Abstract:

Purpose:

Dose deposition measurements for parallel MRI-linacs have previously only shown comparisons between 0 T and a single available magnetic field. The Australian MRI-Linac consists of a magnet coupled with a dual energy linear accelerator and a 120 leaf MLC with the radiation beam parallel to the magnetic field. Two different magnets, with field strengths of 1 and 1.5 T, were used during prototyping. This work aims to characterize the impact of the magnetic field at 1 and 1.5 T on dose deposition, possible by comparing dosimetry measured at both magnetic field strengths to measurements without the magnetic field.

Methods:

Dose deposition measurements focused on a comparison of beam quality ($TPR_{20/10}$), PDD, profiles at various depths, surface doses and field size output factors. Measurements were acquired at 0, 1 and 1.5 T. Beam quality was measured using an ion chamber in solid water at isocenter with appropriate $TPR_{20/10}$ build-up. PDDs and profiles were acquired via Gafchromic film placed in solid water either parallel or perpendicular to the radiation beam. Films at surface were used to determine surface dose. Output factors were measured in solid water using an ion chamber at isocenter with 10 cm solid water build-up.

Results:

Beam quality was within ±0.5 % of the 0 T value for the 1 and 1.5 T magnetic field strengths. PDDs and profiles showed agreement for the three magnetic field strengths at depths beyond 20 mm. Deposited dose increased at shallower depths due to electron focusing. Output factors showed agreement within 1%.

Conclusion:

Dose deposition at depth for a parallel MRI-linac was not significantly impacted by either a 1 or 1.5 T magnetic field. PDDs and profiles at shallow depths and surface dose measurements showed significant differences between 0, 1 and 1.5 T due to electron focusing.

Keywords: MRI-Linac, Parallel orientation, magnetic field, dose deposition

Introduction

Different approaches have been undertaken in integrating MRIs with linear accelerators. The current systems available or under development utilize different magnetic field strengths aiming to balance mutual interactions between the magnetic field and radiation beam including impact on dose deposition and imaging properties[1-7].

The Australian MRI-Linac Program has developed an MRI-linac system with the linac aligned parallel to the B_0 field of a bespoke 1 T split bore MRI scanner. During the development of this system, a 1.5 T Siemens Sonata was installed prior to the acquisition of the 1 T system. A consistent linear accelerator, a Varian Linatron MP, was used in combination with these magnets opening a unique opportunity to compare dosimetric measurements at multiple magnetic field strengths. This work aims to characterize the impact of the magnetic field on dose deposition for a parallel MRI-linac by measuring the dose deposition of the radiation beam from the Linatron at 0, 1 and 1.5 T magnetic field strengths.

Materials and Methods

The Australian MRI-Linac Configuration

Two magnets have been utilized during the development of the Australian MRI-linac system. The initial prototype consisted of a 1.5 T Siemens Sonata magnet (Siemens Healthcare Gmbh, Germany), a dual energy Varian Linatron-MP (Varian Medical Systems, Inc, USA) and a Varian Millennium 120 leaf MLC- which has been described previously[7]. The subsequent system replaced the 1.5 T magnet with a bespoke 1 T split bore magnet (Agilent Technologies Inc. USA). For both systems, the Linatron and MLC were placed on a stainless steel table mounted on a sliding rail and brake system. A source to MR-isocenter distance of 2770 mm was used for all measurements in this work. This distance was selected to reduce the impact of the magnetic field on the Linatron components[8-10]. Field size was defined at this isocenter distance for all measurements. The Linatron has two modes of operation, the 'low' and 'high' mode, utilizing respectively a 4 and 6 MV nominal energy.

Dose Deposition Measurements

The impact of the magnetic field on dose deposition was investigated by five measurements; 1) Energy, investigated via beam quality for both the 4 and 6 MV nominal energy, 2) Percentage Depth Doses (PDD), used to investigate dose deposition along the central axis for only the 4 MV nominal energy, 3) Profiles, used to investigate the dose deposition laterally for only the 4 MV nominal energy, 4) Films placed on the surface, used to evaluate the impact of stray electrons being focused down the bore for the 4 MV nominal energy and 5) Field size output factors, used to investigate differences in scatter contribution to a measurement point for both the 4 and 6 MV nominal energies. The term 'focusing' of electrons down the MRI bore is used in this paper to describe the hotspot of electrons that have been observed to concentrate on the magnetic central axis, reducing in diameter from fringe field to isocenter, for a parallel aligned MRI-linac[7]. All measurements were acquired at 0, 1 and 1.5 T via the same methods. Higher field strength measurements (at 1 and 1.5 T) were compared to measurements at 0 T.

PDD and profile measurements utilized Gafchromic film placed in solid water. Films were processed and analyzed in ImageJ (National Institutes of Health, USA). A single red channel calibration was applied.

Beam quality of the Linatron was characterized for both nominal energies by $TPR_{20/10}$ measurements in solid water, using a 9.2 x 9.2 cm^2 field and a 0.6 cc Farmer chamber set up at the isocenter distance. Uncertainty was calculated via a propagation of the standard deviation of the measurements.

PDD for the 4 MV nominal energy was acquired at 0, 1 and 1.5 T by placing film in-between solid water blocks with the film aligned parallel to the beam central axis for field sizes 3.4 x 2.9, 6.4 x 5.6, 9.2 x 9.2 and 15.2 x 14.7 cm^2. Due to the potential influence of the edge of film on the response of film[11], the initial 2 mm from the film edge was not plotted. PDD were extracted from films via a 3.5

mm wide region of interest along the central axis of the film. To avoid normalization of the PDD in the region where electron focusing was present, PDDs measured at 1 and 1.5 T field strengths were normalized using the 0 T PDD value at 50 mm depth from the equivalent field. Differences between PDD measured at the higher field strengths (1 and 1.5 T) were calculated relative to 0 T. Impact of the magnetic field on PDD was evaluated by calculating the percentage of points from the higher field strength PDDs within 3 % of the 0 T PDD, between the depths of 20 and 200 mm. The difference was evaluated for unfiltered data and after the application of a 3 mm window median filter to reduce the impact of noise. This criterion was determined from the comparison of data acquired on an Elekta Synergy linac using the same measurement and analysis methodology (horizontal beam, surface at isocenter, film placed in solid water on central axis) to water tank scans acquired with a vertical beam in water. Results for the comparison on the Elekta Synergy show the measurement accuracy to be within 2 % of the water tank measured PDD, which is similar to film accuracy quoted in the literature[12,13]. Since we are comparing two separately acquired PDD curves, uncertainty was propagated in quadrature to be 3 %.

Beam profiles for the 4 MV nominal energy were measured using film aligned perpendicular to the beam direction in solid water with the surface at isocenter distance. Field sizes of 3.4 x 2.9 and 9.2 x 9.2 cm^2 were measured at the surface and depths of 10, 54 and 108 mm. Films were centered based on pixel thresholding and profiles extracted for a 3.5 mm wide profile along the center of the field. All profiles were normalized to the 54 mm depth central axis value determined from the PDD measurements. A 3%/2mm 1D global gamma analysis (10 % threshold) was used to evaluate agreement between profiles at different field strengths.

Dose at the surface was calculated for the 4 MV nominal energy via a ratio between surface film and the 54 mm depth film, with the 54 mm depth film normalized to the 0 T PDD value previously measured at this depth. Dose was normalized at 54 mm depth to the 0 T PDD value to avoid normalizing in the dose build-up region where electrons focused down the bore could impact the result. This was equivalent to normalizing to the 0 T d_{max} value within the uncertainty of the film PDD measurements. For all field strengths, the mean and standard deviation for both the surface and 54 mm depth film was calculated from a 3.5 mm^2 region of interest. The region of interest was located on the central axis for films at 0 T and at the point of maximum intensity for films at higher magnetic field strengths. Positioning of the region of interest was consistent for both the surface and 54 mm depth films at the same magnetic field strength. Uncertainty was calculated by propagation of uncertainties.

Field size output factors were measured under isocentric conditions for all magnetic fields using the 4 and 6 MV nominal energy. A Farmer chamber was placed at isocenter with 10 cm solid water build up. Field sizes measured were 6.4 x 5.6, 9.2 x 9.2, 10 x 9.2, 12.2 x 11.4, 15.2 x 14.7, 18.1 x 17.4, 21.1 x 20.6, 24.1 x 23.3, 27.0 x 26.6 and 30.0 x 29.2 cm^2. Field sizes beyond 30 x 30 cm^2 were not measured due to a lack of scatter equilibrium caused by the size of the solid water. The impact of air gaps surrounding the ion chamber in solid water was investigated by measuring the high energy field size output factors with and without water filling the cavity at 1 T.

Results

The Beam Quality ($TPR_{20/10}$) for the 4 and 6 MV nominal energies were equivalent within the calculated uncertainty for 0 and 1.5 T and both higher field strength beam qualities were within ±0.5 % of 0 T (table 1).

An example of the PDDs measured for the 15.2 x 14.7 cm^2 field size for all magnetic fields is shown in figure 1. No filtering has been applied to the PDD in figure 1 as this affected the shape of the PDD at shallow depths where electron focusing has an impact on the dose. Table 2 shows the percentage of points for the higher magnetic field strength PDD within ±3% agreement of the 0 T PDD for different field sizes, for both raw and filtered PDD data. PDD acquired at higher magnetic field strengths showed agreement within ±3 % of the 0 T PDD for above 90 % of points for field sizes at or larger than 6.4 x 5.6 cm^2. Supplementary table 1 shows the depth of dose maximum and percentage depth dose at 50 and 100 mm depth for all field sizes measured at 0 T with the 4 MV nominal energy. Comparison of the initial 20 mm region shows the electron focusing increasing with both magnetic field strengths and radiation field size. Supplementary figure 1 shows the initial 40 mm of the PDD comparison between the 3 different magnetic field strengths, for 4 different field sizes.

Figure 2 shows a comparison between profiles acquired at the surface and depths of 10, 54 and 108 mm in solid water using Gafchromic film for the 9.2 x 9.2 cm^2 field size for all magnetic field strengths. Gamma analysis between profiles measured at higher magnetic field strengths relative to the 0 T profiles showed agreement within 3%/2mm for above 98 % of points for all profiles at or deeper than 10 mm, except between the 0 and 1.5 T profile at 108 mm depth, where 76.3 % of points agreed within 3%/2mm.

Surface dose calculated from the film measurements demonstrates a significant increase with the magnetic field, shown in table 3.

Figure 3 shows differences between field size output factors measured at all magnetic field strengths for the 4 and 6 MV nominal energies. Differences between the measured output factors at 1 and 1.5 T relative to 0 T were less than 1 % for both nominal energies. Supplementary figure 2 shows the measured field size output factors. Differences between high energy field size factors, measured at 1 T, with and without water surrounding the ion chamber were within ±0.5 %.

Discussion

In this work we have investigated the differences in beam properties measured for an MRI-Linac orientated with the radiation beam parallel to the magnet B_0 axis for multiple magnetic field strengths.

Beam quality was observed to not be impacted by magnetic field strength with difference in the measured $TPR_{20/10}$ less than 0.5 %. The suggested clinical tolerance relative to baselines for beam quality temporal stability is ± 1.0 % for clinical beams[14]. O'Brien et al[15] showed measured $TPR_{20/10}$ beam qualities were independent of magnetic field on a MRI-linac with a beam direction perpendicular to the B_0 magnetic field.

PDD acquired at 1 and 1.5 T were predominately within ±3 % of 0 T PDD beyond a depth of 20 mm. Filtration of the PDD data showed improvements in agreement for the smallest field indicating that noise in the film analysis impacted the results. Monte Carlo simulations of a 10x10 cm^2 beam on a cylindrical water phantom in 0 and 1 T magnetic fields showed no significant differences in dose deposition, with the only differences observed appearing to be random[16]. Our results are also consistent with simulations and mathematical proofs of the magnetic field not impacting the dose deposition for broad beams aligned parallel to the magnetic field[17]. Differences observed between PDD acquired at 1 and 1.5 T relative to 0 T were similar to differences observed between water-tank and film PDD collected on an Elekta linear accelerator in no magnetic field. The increase in dose at shallow depths was due to a focusing of electrons due to the B_0 fringe field, which was shown to increase with both field size and the magnitude of the magnetic field. This is in line with previously published Monte Carlo calculations[18]. It is important to note that electron focusing is dependent on both the magnitude and shape of the fringe field[18,19]. Prior simulations of dose deposition within parallel magnetic fields have either used uniform magnetic fields[16,17], simplified fringe field models[18] or realistic simulations of a 0.56 T parallel aligned linac[19].

Normalizing the dose at depth, in this instance 50 mm, was necessary to compare PDDs and profiles between magnetic field strengths, as the dose maximum is within the electron contamination region.

Comparison of profiles measured for a 3.4 x 2.9 cm^2 and 9.2 x 9.2 cm^2 fields at 0, 1 and 1.5 T showed at least 98 % agreement within 3%/2mm for both field sizes at depths of 10, 54 and 108 mm. The one exception was the comparison between the 0 and 1.5 T beam at 108 mm depth for the 3.4 x 2.9 cm^2 field. A difference just over 3 % was seen between the 0 and 1.5 T profiles for a number of points within the center of the field, resulting in the low gamma value. This was likely due to a lower dose delivered to the 1.5 T film increasing uncertainty.

Surface doses measured at higher magnetic field strengths were observed to considerably increase relative to the 0 T surface dose. An earlier version of Gafchromic film has previously been used to measure surface dose with accuracy comparable to Attix chambers[20]. Both the PDD and profile measurements show an increase in central axis surface dose with increasing field size due to electron focusing. As observed in the surface profiles, the maximum surface dose was not necessarily located along the central axis. The maximum surface dose most likely corresponds to the central axis of the B_0 field, which may be offset from the mechanical center of the magnet bore due to the asymmetrical shape of the fringe field upstream from the phantom surface. Additionally, alignment of the radiation beam and MLC to the mechanical center of the bore could cause an offset in the center of the field relative to the center of the bore. At 1 T, the surface dose increased by a factor of 4.2 and 5.5 for the 3.4 x 2.9 cm^2 and 9.2 x 9.2 cm^2 field sizes respectively. At 1.5 T, the surface dose increased by a factor of 6.9 and 10 for the 3.4 x 2.9 cm^2 and 9.2 x 9.2 cm^2 field sizes respectively. Previous modelling of entrance doses to a phantom has shown a dependence on separation between the magnet and linear accelerator as well as fringe field shape[18]. Simulated surface dose values in the literature have ranged between 20 – 600 % of the dose at d_{max} for similar sized fields[18,19]. This previous work did not simulate the field size, coil geometry distances and fringe field measured in our work and therefore does not provide a valid comparison to our data. The variation in simulated surface dose in the literature highlights the need to measure surface dose on MRI-linacs. Uncertainty in the measured surface dose increased with magnetic field due to a high standard deviation in the 3.5 mm^2 region of interest surrounding the maximum intensity position. The higher standard deviation was due to the increased sharpness of the peak which can be observed in the surface profiles presented in figure 3. The significant increase in surface dose associated with the magnetic fringe field shape and strength needs to be considered when designing a parallel geometry MRI-linac. Entrance dose shows a significant reduction when measured in the 1 T magnetic field relative to the 1.5 T field. Increased entrance dose due to the magnetic field has also shown a dependence on the field size. The use of smaller field sizes or segments in IMRT fields can serve to reduce the entrance dose for parallel magnetic field systems without active or passive shielding that have large fringe fields. However, the efficiency of the delivery and the accuracy of the treatment planning system would also need to be evaluated and considered for the smaller field sizes[21].

Comparison of output factors showed changes of less than 1 % between factors measured at all magnetic field strengths. The agreement of the output factors indicate that the scatter contribution to the measurement point from both the linac head and phantom scatter has not significantly changed with the magnetic field. No correlation between output factors and magnetic field strength was observed.

Comparisons between 0, 1 and 1.5 T measurements of the beam quality, PDD, profiles and output factors indicate that the magnetic field has minimal impact on dose deposition in water equivalent material beyond 20 mm depth. At shallower depths the focusing of electrons by the magnetic field was observed to cause increased dose in the build-up region along the central axis. These measurements confirm previously simulated results of the magnetic field impact on dose deposition in a parallel geometry[17,18].

Air gaps surrounding chambers in solid phantoms have been shown to cause issues for perpendicular magnet and radiation source geometries[22-25]. The influence of air gaps surrounding the ion chamber in our measurement set-up was observed not to impact the calculated total scatter factors. This validates our ion chamber and solid water set-up only. Further work quantifying the impact of air gaps surrounding dosimeters is required. To the best of the authors' knowledge at the time of writing, no simulations or experimental investigations have been conducted into the dosimetric impact of an air gap surrounding an ion chamber in a parallel geometry.

EBT3 film was used for measuring both PDD and profiles in the magnetic field. The magnetic field impact on EBT3 film response has been deemed negligible[26,27]. Additionally, potential response changes due to the magnetic field for film measurements in this study would be minimized due to the normalization of the film measurements between different magnetic field strengths.

The magnetic field could theoretically have had an impact on the linac components[8-10]. The magnitude of the magnetic field measured at the target of the linac was less than simulated values where the fringe field was shown to impact beam generation[8-10]. The results presented here are therefore generalizable to any parallel orientation MRI-linac provided the linac component is magnetically de-coupled from the MRI.

Setting up beam characterization measurements for a horizontal beam presented some unique challenges not normally observed during conventional linac commissioning. Comparison between horizontal film measurements and vertical water tank setups on a convention linear accelerator[28] ensured the methodology used to collect the Linatron PDDs and profiles was accurate. Due to the metallic components and size restrictions, water tank equipment could not be used on the MR-linac. Therefore beam data collection in the magnetic field was limited to Gafchromic film measurements and ion chamber point measurements in solid water.

Conclusion

The measurements presented in this work characterized differences in dose deposition in the presence of magnetic fields parallel to the radiation beam. Beam quality, percentage depth dose, profiles, surface dose and field size output factors were measured at magnetic field strengths of 0, 1 and 1.5 T. Beam quality measurements were not impacted by the magnetic field. PDD measurements showed significant differences in dose deposited at shallow depths for the different magnetic fields. At depths greater than 20 mm, the PDD measured for the different magnetic fields showed agreement within ±3 % of the 0 T PDD for above 90 % of points for field sizes at or larger than 6.4 x 5.6 cm^2. Profile measurements of the lateral dose deposition showed agreement within 3%/2mm at larger depths. Surface dose measurements, from films placed on the surface of a water phantom, showed the most significant impact of magnetic fields aligned parallel to the radiation beam direction due to the focusing of electrons onto the entrance of the phantom. Measured surface dose was lower for the 1 T field relative to 1.5 T. Surface dose values of 191 % and 345 % were measured for a 9.2 x 9.2 cm^2 field for magnetic field strengths of 1 and 1.5 T respectively. Field size output factors showed agreement within 1 % between the different magnetic fields.

The results have demonstrated the significant impact that a magnetic field aligned parallel to the direction of the beam can have on dose deposition in water at shallower depths, whilst also demonstrating how the dose deposited in water at depth remains relatively unimpacted by the magnetic field.

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Disclosure of Conflicts

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Figure 1: PDD measured using Gafchromic film for the 15.2 x 14.7 cm^2 field size at magnetic field strengths of 0, 1 and 1.5 T for 4 MV beam energy. PDD at 1 and 1.5 T were normalised to the 0 T PDD at 50 mm depth.

Figure 2: Profiles measured in solid water using Gafchromic film aligned perpendicular to the beam direction at the surface and depths of 10, 54 and 108 mm for the 9.2 x 9.2 cm^2 field size. Note, the films were normalized at the percentage depth dose measured at a depth of 54 mm.

Figure 3: Difference between isocentric field size output factors measured at 1 and 1.5 T relative to 0 T for the low (A) and high (B) mode. Values for field size output factors are shown in supplementary figure 2.

Nominal Energy (MV)	0 T	1 T	1.5 T
4	0.589 (± 0.001)	0.586 (± 0.009)	0.591 (± 0.001)
6	0.634 (± 0.003)	0.632 (± 0.007)	0.635 (± 0.003)

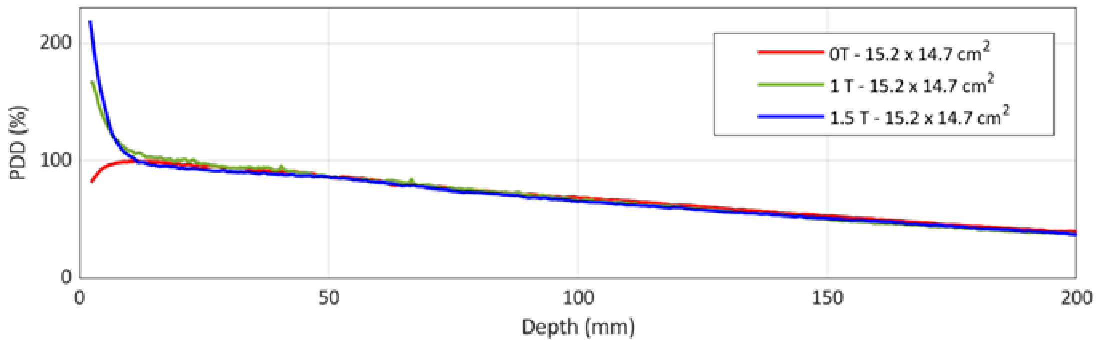
Table 1: Beam Quality ($TPR_{20/10}$) measured for the 4 and 6 MV nominal energies at 3 different magnetic field strengths

Filter	Field Strength	3.4 x 2.9 cm^2	6.4 x 5.6 cm^2	9.2 x 9.2 cm^2	15.2 x 14.7 cm^2
Unfiltered	1 T	66.1%	92.8%	94.7%	92.7%
	1.5 T	51.8%	100.0%	100.0%	99.4%
Median (3 mm)	1 T	80.0%	92.0%	92.9%	95.1%
	1.5 T	69.8%	100.0%	100.0%	99.4%

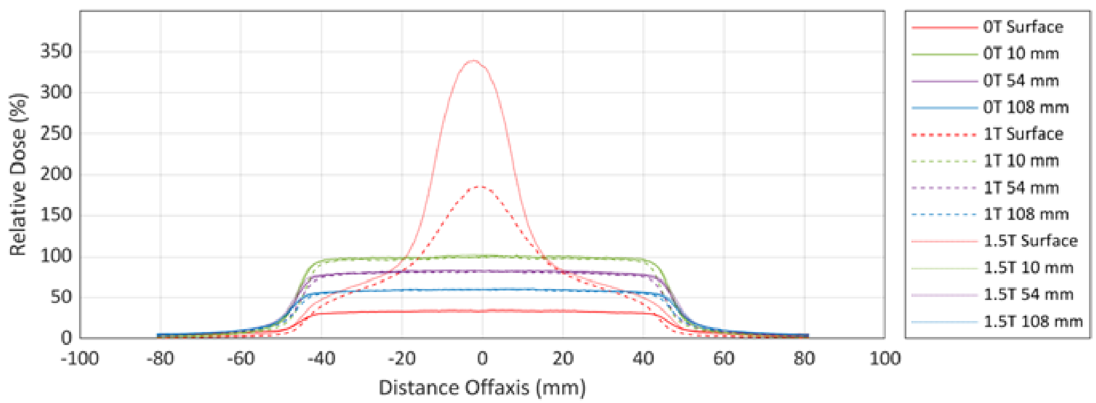
Table 2: Percentage number of points from PDD acquired at higher magnetic field strengths (1 and 1.5 T) within 3 % of the PDD acquired at 0 T.

Field Size	0 T	1 T	1.5 T
3.4 x 2.9 cm^2	28.8 ± 2.3 %	118.4± 9.6 %	198.6 ± 15.9 %
9.2 x 9.2 cm^2	34.6 ± 2.5 %	190.6 ± 13.9 %	345.4 ± 25.6 %

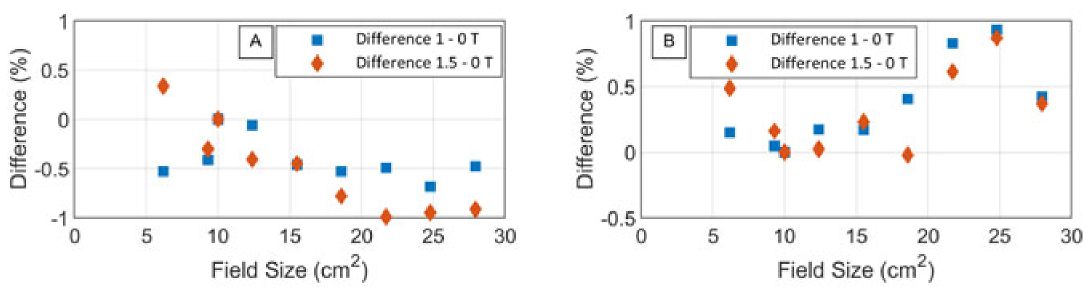
Table 3: Surface dose, relative to the maximum dose at 0 T, measured at different magnetic field strengths for the 3.4 x 2.9 cm^2 and 9.2 x 9.2 cm^2 field size. Surface dose was calculated on the central axis for 0 T, and at the maxima of the surface films for 1 and 1.5 T.



PDD (%)
200
100
0
0
50
100
150
200
Depth (mm)
0T - 15.2 x 14.7 cm2
1 T - 15.2 x 14.7 cm2
1.5 T - 15.2 x 14.7 cm2



Relative Dose (%)
350
300
250
200
150
100
50
0
-100
-80
-60
-40
-20
0
20
40
60
80
100
Distance Offaxis (mm)
0T Surface
0T 10 mm
0T 54 mm
0T 108 mm
1T Surface
1T 10 mm
1T 54 mm
1T 108 mm
1.5T Surface
1.5T 10 mm
1.5T 54 mm
1.5T 108 mm



A
Difference 1 - 0 T
Difference 1.5 - 0 T
Difference (%)
1
0.5
0
-0.5
-1
0
5
10
15
20
25
30
Field Size (cm2)
B
Difference 1 - 0 T
Difference 1.5 - 0 T
Difference (%)
1
0.5
0
-0.5
0
5
10
15
20
25
30
Field Size (cm2)