Impact of a Parallel Magnetic Field on Radiation Dose Beneath Thin Copper and Aluminum Foils

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Abstract

Purpose:

The RF coils for magnetic resonance image guided radiotherapy (MRIgRT) may be constructed using thin and/or low-density conductors, along with thinner enclosure materials. This work measures the surface dose increases for lightweight conductors and enclosure materials in a magnetic field parallel to a 6MV photon beam.

Methods:

Aluminum and copper foils (9-127µm thick), as well as samples of polyimide (17µm) and polyester (127µm) films are positioned atop a polystyrene phantom. A parallel plate ion chamber embedded into the top of the phantom measures the surface dose in 6 MV photon beam. Measurements (% of dose at the depth of maximum dose) are performed with and without a parallel magnetic field (0.22T at magnet center).

Results:

In the presence of a magnetic field, the unobstructed surface dose is higher (31.9 $\%D_{max}$ vs 22.2 $\%D_{max}$).

The surface dose is found to increase linearly with thickness for thin (<25 µm) copper (0.339 $\%D_{max}\mu m^{-1}$) and aluminum (0.116 $\%D_{max}\mu m^{-1}$) foils. In the presence of a magnetic field the slope is lower (copper: 0.16 $\%D_{max}\mu m^{-1}$, aluminum: 0.06 $\%D_{max}\mu m^{-1}$). The effect of in-beam foils is reduced due to partial shielding of the surface from contaminant electrons. Copper causes a surface dose increase ≈3 times higher than aluminum of the same thickness, consistent with their relative electron density. Polyester film (127µm) increases the surface dose (to 35% D_{max} with field) about as much as a gown (36% D_{max} with field), while the increase with polyimide film (17μm) is less than 1% above the open field dose.

Conclusions:

Thin copper and aluminum conductors increase surface dose by an amount comparable to a hospital gown. Similarly, enclosure materials made of thin polyester or polyimide film increase surface dose by only a few %D_{max} in excess of an unobstructed beam. Based on measurements in this study, in-beam, surface RF coils are feasible for MRIgRT systems.

Keywords

Linac-MR Hybrid, Surface Dose, Magnetic Field

1) Introduction

Magnetic resonance image guided radiotherapy (MRIgRT) has the potential to deliver state-of-the-art radiation therapy concurrently with soft-tissue imaging.[1–5] Because radio frequency (RF) coils provide maximal signal to noise ratio (SNR) in MRI when placed closest to the imaged region, these coils may need to be placed in the path of radiation beam(s) treating the same region. While it is possible to use RF coils placed far enough away to avoid intersecting the beam path or to treat only from angles that do not irradiate the coil,[6,7] image SNR or treatment plan quality, respectively, may suffer. For the RF coil designs that do intersect the radiation beam, it is important to understand the dosimetric consequences of materials intersecting the beam in a magnetic field.

While previous studies have shown minimal impact of RF coils in the beam on the target volume dose,[8,9] only one study has investigated the impact on the surface dose.[8] A stack of materials simulating an RF coil placed in the beam, in contact with a phantom surface, increases the surface dose to >75% of maximum dose (D_{max}).[8] This example coil consisted of a polycarbonate base (1.5 mm), copper tape conductor (0.08 mm), and PTFE (Teflon®, 0.9 mm) cover. The increase was measured with the magnetic field both parallel and perpendicular to the beam, as well as without field. The authors also found a surface dose increase to 45% D_{max} (48% D_{max} in a parallel magnetic field from a 0.22 T magnet) for 0.1 mm copper plate alone.[8]

The surface dose increases due to the low energy secondary electrons, produced by photons interacting with coil's materials, depositing their energy in the superficial layers of a phantom or patient below (bolusing effect). In this reference[8], and a follow up study comparing measurements to Monte Carlo simulations[10], Ghila et al. also found that the surface dose increased in the presence of a parallel magnetic field even when nothing was obstructing the beam path. The surface dose was ~20% D_{max} without the field, and ~30% D_{max} in the presence of the field.[8,10] This effect is caused by contaminant electrons (produced in the linac head and irradiated air column) being trapped and guided by Lorentz forces due to the magnetic field.[8,10] Similar effects have been simulated and measured in other studies of MRIgRT systems.[11–13] Note that, for such parallel systems, the strength of the field at the surface is not as important as the strength and shape of the fringe field near the linac head and the air column. The exact shape of the field determines where on the surface the contaminant electrons contribute dose.

The interest in surface dose is motivated by skin reactions that occur in radiation therapy. Even in traditional fractionated treatments, low levels of acute skin reactions are common with the skin receiving a fractionated dose of 2-8 Gy.[14] For every doubling of absorbed skin dose, the degree of acute skin damage increases by one step: from discoloration, to erythema, to desquamation, up to necrosis at 40 Gy fractionated. Additionally, increased dose to skin raises the risk of long-term effects of radiation dose and their severity.[14]

Large increases in surface dose due to in-beam RF coils can, however, be reduced. The predominantly Compton interactions in therapeutic photon energy range depend on electron density (e^-/cm^3).[15] Since electron mass density (e^-/g) varies slowly with atomic number, the number of Compton interactions depends on the amount of material (thickness) and its density. Thin ($\ll$0.1 mm) and/or lower density conductors in RF coils thus may allow in-beam coils to be placed directly on the patient surface without a large increase in skin dose.[8] Lightweight RF coils that use conductive inks,[16,17] thinner conductors,[18] and minimal enclosures are already being designed for a variety of purposes. Conductors made of aluminum instead of copper have also been considered because of the lower density.[18,19]

This work fills a gap in the literature by presenting surface dose measurements, with and without a parallel magnetic field, below various thicknesses (9–127 μm) of copper and aluminum, and insulating materials that could be used as enclosures for in-beam RF coils.

2) Materials and Methods

The surface dose below square (10 × 10 cm^2) copper and aluminum foils of thicknesses ranging from 9 to 127 μm was measured using a PTW Markus parallel plate ion chamber (PTW, Freiburg, Germany). Additionally, the surface dose was measured below a polyimide film (17 μm thick, Kapton®, DuPont, Wilminton, DE, USA) and a polyester film (127 μm thick, HP LaserJet transparency, Hewlett-Packard Company, Palo Alto, CA, USA). Polyimide is a common substrate for flexible printed circuit boards (PCBs). The polyester film is a potential lightweight enclosure material for flexible RF coils. For comparison, the surface dose below a hospital gown was also measured.

Each sheet was positioned in contact with the top surface of a solid polystyrene phantom which simulated tissue and provided backscatter. The parallel-plate ion chamber was set into the phantom top surface[8] with its effective point of measurement being just below the entrance window (0.03 mm polyethylene). The sheets were irradiated with a square 8.5 × 8.5 cm^2 (source to phantom surface distance or SSD = 170 cm) 6 MV beam from a Varian Silhouette linac (Varian Medical Systems, Palo Alto, CA) with and without the presence of a parallel magnetic field. Dual solenoid electromagnets (model 3472-70, GMW Associates, San Carlos, CA), placed on a wooden stage on the floor, generated a 0.22 tesla (T) field at the center of their bore decreasing to 0.6 mT at the linac's exit window.[8,10] A detailed description of the field for this specific magnet setup can be found in Ghila et al. 2017.[10] The polystyrene phantom was positioned inside the bore of the electromagnets such that the top surface of the phantom coincided with the top of the solenoids (Figure 1).

Surface dose was determined as the ratio of ionization in the ion chamber at the surface to the maximum ionization (D_{max}) in the phantom. Readings were taken at 1.4 cm, 1.5 cm and 1.6 cm depths, below stacks of polystyrene sheets, to sample the depths where maximum ionization (D_{max}) is expected. D_{max} was measured with and without a magnetic field. The ratio of ionizations is reported as a percent of D_{max} (% D_{max}). This chamber and set-up has been validated in previous studies.[8,10]

Measurements were performed over several days and repeated measurements were averaged. For thin foils (thickness ≤ 25 μm) linear regression was used to fit the surface dose increase for copper and aluminum with and without a field. The p-value was used to evaluate the goodness of the fit.[20] P-value is based on the χ-square test and gives the probability that a data set with a worse misfit (higher χ-square) would be obtained assuming the fit is correct. A very low p-value ($\ll 0.01$) signifies a poor fit, while a very high p-value (>0.99) suggests overfitting, or overestimated data errors. The 95% confidence interval was used as the error in the slope.

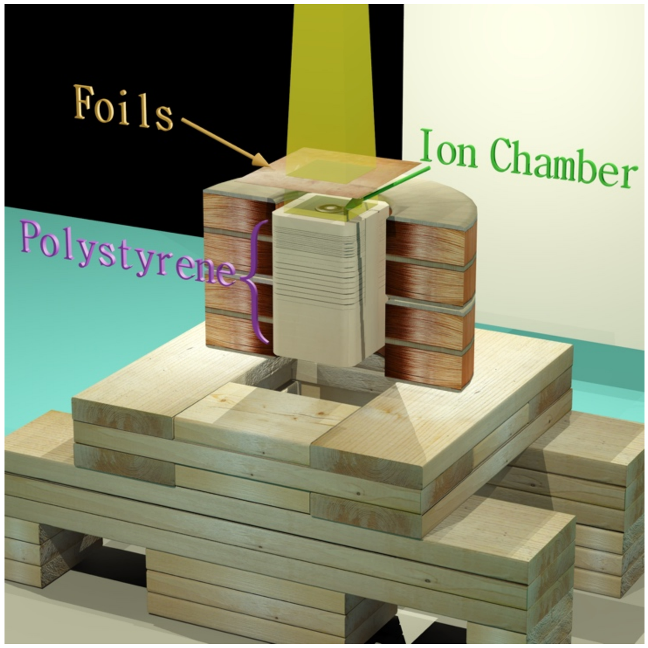

Figure 1: Surface dose was measured below copper and aluminum foils of various thicknesses. The foils were placed in the beam on top of the polystyrene phantom surface with an inset parallel plate ion chamber. Foils were in direct contact with the phantom surface (gap in image is introduced to show the ion chamber). The phantom was inside the bore of dual solenoid electromagnets positioned on top of a wooden support structure.

3) Results

The average surface doses for an unobstructed beam were 22.2 ± 0.1 % and 31.9 ± 0.2 % of D_{max} with no field and with the magnetic field respectively.

The measured surface dose increases due to copper and aluminum are shown in Figure 2, showing an approximately linear relationship for thicknesses ≤ 25μm. Surface dose increases by 0.339 ± 0.008 $\%D_{max}$ μm^{-1} for copper (χ^2 = 15.6, p = 0.0004) and 0.116 ± 0.006 $\%D_{max}$ μm^{-1} for aluminum (χ^2 = 8.99, p = 0.174) with no field; and by 0.16 ± 0.01 $\%D_{max}$ μm^{-1} for copper (χ^2 = 0.132, p = 0.936) and 0.06 ± 0.01 $\%D_{max}$ μm^{-1} for aluminum (χ^2 = 0.165, p = 0.999) with field. Slopes are obtained by linear regression with the open-field dose being a fixed zero-intercept. With the exception of the no field copper data, the p-values suggest that the datasets match a linear trend reasonably well.[20] For copper (no field) the extremely small p-value (4×10^{-4}) indicates a poor model fit given the small (1%) uncertainty of the measurements. This may be due to the limited number of points for thin copper foils, or that the linearity approximation breaks down in this case. Measurements of surface dose below a hospital gown, polyimide (17 μm), polyester (127 μm) are listed in Table 1. The surface dose increase due to the polyester film is comparable to the increase caused by a hospital gown. The 17 μm polyimide had a very small impact on the surface dose similar to that of 15 μm aluminum; with either one of these, the surface dose (with field) is within 1 $\%D_{max}$ of the surface dose (with field) of an unobstructed beam.

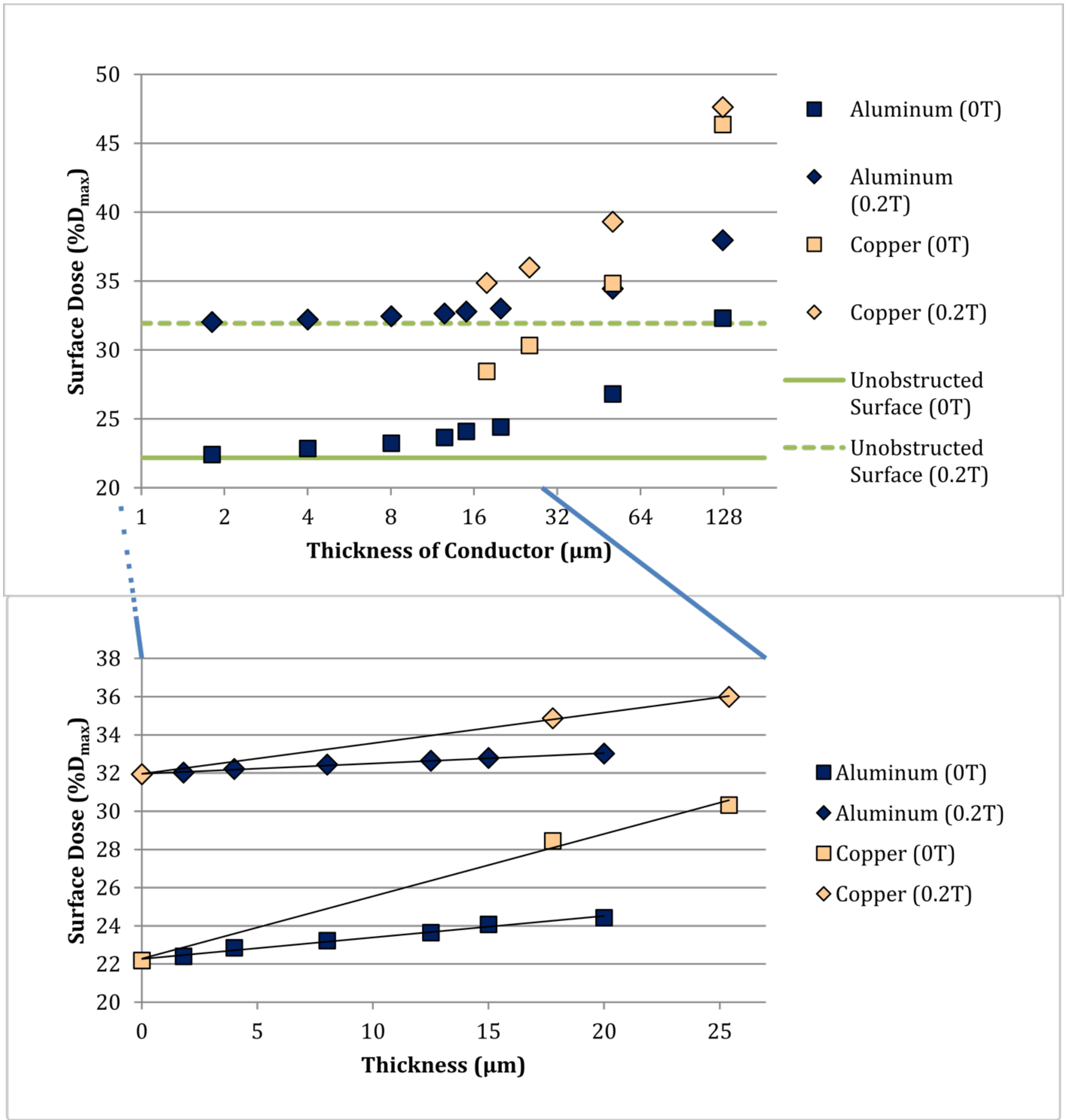

Figure 2: (Top) Surface dose measured below copper and aluminum sheets of various thicknesses (logarithmic scale). The unobstructed surface doses were 22%D_{max} (solid horizontal line) and 32%D_{max} (dashed line) without and with a parallel magnetic field (0.22 T magnet) respectively. Uncertainty in each data point is less than 1% (.2% D_{max}). (Bottom) The linear region (0 to 25 µm) is expanded and shown on a linear scale and with linear fits. The slopes are 0.116 %D_{max} μm^{-1} (no field, marked 0T) and 0.06 %D_{max} μm^{-1} (with field, marked 0.2T) for aluminum, and 0.339 %D_{max} μm^{-1} (no field) and 0.16 %D_{max} μm^{-1} (with field) for copper.

Material	Surface Dose with No Field (%D_{max})	Surface Dose with Field (%D_{max})
Open Field	22.2	31.9
Hospital Gown	28.3	36.0
Polyimide (17 μm)	23.7	32.7
Polyester (127 μm)	28.5	35.9

Table 1: Surface dose for support and enclosure materials positioned in the beam.

4) Discussion

The magnitude of the increase in the surface dose, for an unobstructed beam, due to the magnetic field (from 22.18% D_{max} to 31.9% D_{max}) is dependent on the specific magnetic field pattern[12,21,22] between the linac head and the phantom surface. As other studies have found[8,11–13,21,22], the parallel magnetic field in general leads to surface dose increases due to trapping of contaminant electrons. Adding coil conductors (≤25 μm) in the beam causes the surface dose to increase proportionally to the thickness of copper and aluminum as confirmed by the goodness of fit. For thicker conductors the proportionality breaks down because they partially self-shield, with downstream segments of the foil absorbing some of the electrons produced upstream in the same foil.

Interestingly, the slopes of the fits in a magnetic field are lower than those without a magnetic field. This is because the metal sheets shield the surface from contaminant electrons captured by the magnetic field. A thicker sheet, while increasing the dose due to a greater build-up (bolusing effect), will also better shield the surface from upstream contaminant electrons captured by the parallel magnetic field. This means the effect of material in the beam is reduced in the presence of the magnetic field compared to the open field dose. The ratio of slopes between copper and aluminum (2.9±0.2 with no field, 2.9±0.7 with field) is consistent with the ratio predicted by the relative electron density of the two metals (3.1)[23].

Measuring the surface dose below a hospital gown allows us to compare the effect of the metal foils to a material typically considered negligible. Copper ≤ 25 μm, and aluminum ≤ 50 μm thick increase the surface dose less than a hospital gown does. The conductors of RF coils can thus be made to have a negligible effect on the surface dose.

Additionally, the enclosures for RF coils need not increase the surface dose to 83% of D_{max} as traditional enclosures do.[8] Thin (17 μm) polyimide increases surface dose by little over 1% (compared to an unobstructed beam). If enclosing polyimide layers are considered insufficient, a layer of polyester (127 μm), while increasing the dose more than a hospital gown, is still dramatically less impactful on the surface dose than traditional housings (4-6.3% D_{max} increase vs. ~60% D_{max} increase).[8]

Surface dose increases due to material in the beam are consistent with previous results.[8] These measurements are specific to the field shape and strength used. Exact surface dose increases will differ for other magnetic fields, although the general trends are expected to be similar. As an extreme example, in perpendicular field the effect of coils positioned on the surface would be close to that measured for the no field case. This is because there is no surface dose increase due to contaminant electrons as they are swept away rather than trapped by the magnetic field. However, the increased surface dose due to the bolusing effect will still be present for surface RF coils regardless of magnetic field configuration or strength.

The measurements in this study were performed on foils that were slightly larger than the radiation field size to allow for reliable comparisons between thicknesses and materials. In reality, surface RF coils are constructed of narrow strips of foil and thus these surface dose measurements represent upper bounds. The introduction of air gaps that would be present in rigid volume coils will further reduce the surface dose increase, especially in perpendicular magnetic fields, where a large enough gap can eliminate the bolusing effect completely.[8,24] This data also suggests that evaluating the surface dose impact should be an integral part of the design procedure for RF coils used in the radiation beam of MRIgRT systems.

5) Conclusions

As advancements are made in MRIgRT, RF coils will continue to be critical components in effective treatments and imaging. It is impractical to expect that every MRIgRT treatment plan will avoid beam(s) passing through the RF coil. The introduction of materials in the path of the radiation beam leads to measurable increases in patient surface dose that can have serious consequences. Surface coils will increase entrance surface dose regardless of magnetic field strength, or configuration (transverse or parallel) due to the bolusing effect. This study shows that there are thicknesses of copper and aluminum that provide markedly lower surface dose than traditional coils. Additionally, there are some practical enclosure materials that interact with the beam on the same order or less than a hospital gown.

For thin materials the surface dose increase is found to be proportional to thickness and electron density of the material. Therefore, using thin (≤ 25 μm) and/or lower density materials (aluminum rather than copper), allows RF coils to be placed on the surface, in the path of the radiation beam, without having a significant impact on surface dose.

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Conflict of Interest Disclosure

One of the authors, Dr. Fallone, is a co-founder and chairman of MagnetTx Oncology Solutions.

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