Case study with dosimetric analysis: Total Body irradiation to a patient with a left ventricular assist device

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Purpose: This case report discusses the safe delivery of total body irradiation (TBI) to a patient with a left ventricular assist device (LVAD). This treatment required radiation-dose determinations and consequential reductions for the heart, LVAD, and an external controller connected to the LVAD.

Methods: The patient was treated using a traditional 16MV anterior posterior (AP)/posterior anterior (PA) technique at a source to surface distance (SSD) of 515cm for 400cGy in two fractions. A 3cm thick Cerrobend block was placed on the spoiler to reduce dose to the heart and LVAD to 150cGy. The external controller was placed in a 1cm thick plastic box to reduce neutron dose and positioned as far away as possible, just outside the treatment fields. In vivo measurements were made using optically stimulated luminescence dosimeters (OSLDs) placed inside the box at distances of 2cm, 8.5cm, and 14cm from the field edge, and on the patient along the central axis and centered behind the LVAD block. Further ion chamber measurements were made using a solid water phantom to more accurately estimate the dose delivered to the LVAD.

Results: The total estimated dose to the controller ranged from 135.3cGy to 91.5cGy. The LVAD block reduced the surface dose to the patient to 271.6cGy (68.1%). The block transmission factors of the 3cm Cerrobend block measured in the phantom were 45% at 1cm depth and decreased asymptotically to around 30% at 3cm depth. Applying these transmission factors to the in vivo measurements yielded a dose of 120cGy to the implanted device.

Conclusion: Physical limitations of the controller made it impossible to completely avoid dose. Shielding is recommended. The block had limited dose reduction to the surface, due to secondary particles, but appropriately reduced the dose at 3cm and beyond. More research on LVADs dose limits is required.

Introduction

There is no cure for end stage heart failure. Currently, the only viable long-term treatment is a heart transplant. Among the absolute contraindications for a heart transplant is the presence or history of cancer (most types) within the previous 5 years due to concerns about active disease. An further complicating issue is the known cardiotoxicities of cancer therapies, including radiation, chemotherapy, and immunobiologics, all exacerbated by pre-existing cardiac morbidities[1,2]. Left ventricular assist devices (LVADs) help to improve survival rates in cases of heart failure and can be used as a bridge to transplant candidacy and ultimately receiving a transplant. An LVAD is an implanted mechanical pump which is directly attached to the left ventricle of the heart. The pump continuously pushes blood out of the ventricle to the aorta and the rest of the body. The LVAD consists of the mechanical pump as well as an external controller attached by a short driveline cable, 100cm in total length. Generally, the pump is powered by batteries located externally to the patient. The device can also be directly plugged into an electric outlet, if needed. As LVAD technology improves, more patients are having them implanted and survival rates with them are increasing. This leads to a growing number of patients concomitantly afflicted with cancer. To bridge patients to transplant

candidacy, radiation is frequently used as part of the multidisciplinary approach to treatment.

Radiation is well known to damage electronics. While the effect of radiation on other cardiac implantable electrical devices (CIED), including pacemakers and defibrillators, has been well studied, there remains limited data on radiation to LVAD[3-7]. Much of the existing radiation data is in the form of in-vitro studies and case reports[8-15]. None of these studies considered the radiation sensitivity of the LVAD external controller. Here, we report the first case of dose delivered to the controller and the first reported case of total body irradiation (TBI) to a patient with an LVAD.

The nature of TBI treatments makes this an especially challenging case. The goal of the TBI is to eliminate the leukemia cells within the bone marrow, as well as suppress the immune system in order to decrease the potential for transplanted hematopoietic stem cell rejection. Traditional TBI techniques use opposing fields, AP/PA or laterals, to deliver a therapeutic dose. This does not allow for the same level of precise dose delivery as more advanced treatment techniques for localized cancers. This creates a tradeoff between limiting dose to the LVAD while ensuring sufficient dose to the surrounding bone marrow. In addition, these TBI treatments utilize large open radiation fields with sufficient flash to cover the entire patient. This is quite different from the majority of case reports in localized radiotherapy where the LVAD controller is usually far away from the radiation field. Even outside of the direct radiation field, there is out-of-field dose to consider from scatter dose and linear accelerator leakage. As a result, the external controller cannot be completely removed from all radiation. This report details the treatment approach used to manage this complex patient.

Furthermore, accurately assessing the dose delivered to the LVAD during a TBI poses unique challenges. In-scatter, back-scatter, and electron contamination all contribute to uncertainty in dose calculations[16,17]. In addition, there is a lack of information on out-of-field doses in treatments with extended SSDs such as TBI treatments[18]. Therefore, direct measurements are necessary to estimate dose to the LVAD and the external controller.

Methods and Materials

Patient Background

The patient in this case study is a 36-year-old male, with a history of acute myeloblastic leukemia. Chemotherapy is believed to have caused cardiomyopathy leading to cardiogenic shock with an ejection fraction of 18% and the subsequent need for a left ventricular assist device (LVAD). To bridge the gap to transplant candidacy, the patient was implanted with an Abbot HeartMate 3 LVAD approximately 5 months prior to radiation treatment[19,20].

TBI Simulation

The patient was simulated and treated using a traditional 16 MV anterior posterior (AP)/posterior anterior (PA) technique. High energy x-rays (>10MV) produce less dose variation form the central axis[17]. However, known neutron contamination in high energy x-rays is detrimental to electronics[21,22]. At the time of treatment, alternative TBI treatments using 6MV were not commissioned in our clinic. As such, the patient was classified as high-risk and associated recommendations made in the report of AAPM Task Group 203 were followed, including having members of the cardiology team present for every treatment[4].

During simulation, the patient laid on their left side facing the treatment machine. A 2.54cm thick acrylic beam spoiler was placed in front of the patient near the skin surface to increase the surface dose in the build-up region at a source-to-surface distance of 500 cm, simulating the AP treatment. The patient was then positioned such that the distance from the spoiler to their umbilicus was 15cm. Measurements of the patient's thickness were acquired at the umbilicus, head, neck, shoulder, mediastinum, hip, mid-thigh, knee, and ankle. The midline separation was measured to be 26cm. Off-axis distances and the spoiler-to-patient separation were also measured for each anatomical landmark. Planar imaging was done with 16MV beams and film in this position to ascertain the position of the heart and LVAD within the patient. This entire

process was repeated with the patient on their right side facing away from the machine to simulate the PA treatment. The PA simulation setup of the patient is shown in Figure 1A

The patient was prescribed 400cGy to the midline in two 200cGy daily fractions, with the AP and PA fields equally weighted.

After careful discussion about the patient's safety, the area encompassing the LVAD and heart was prescribed a reduced total dose of 150cGy (37.5% prescription), which was the minimum that would be achievable due to scatter dose from behind the Cerrobend block. The size and shape of the Cerrobend was determined by the physician based on the planar imaging acquired during simulation. An in-house TBI calculator was used to calculate the necessary thickness of lead compensators to optimize dose homogeneity at each anatomical site measured and the required thickness of Cerrobend to block the heart and LVAD (LVAD block). From this, the LVAD block was calculated to be 3 cm thick. Lead compensators were fabricated out of 1.69mm thick lead sheets to be attached to the gantry mount.

Treatment

Both treatment fields were 40x12cm^2 with the collimator set to 90 degrees. The LVAD was switched from battery power to external power to minimize the chance of power disruption during the treatment. As shown in Figure 1B, the external controller for the LVAD was placed inside a 1cm thick plastic box to reduce neutron dose and positioned outside the treatment field above the patient such that the field edge was approximately coincident with bottom of the box. The controller could not be moved any further out of the field due to the finite length of the driveline cable connecting it to the rest of the LVAD. High-Z shielding was not used due to the concern of creating secondary particles. The appropriate LVAD block was placed on the beam spoiler for each treatment field. Figure 1B shows the placement of the AP block. Planar film imaging was used to confirm the position of the block. If necessary, the position of the block was adjusted, and imaging was repeated. For the first fraction, in vivo measurements were obtained by placing two Landauer nanoDot optically stimulated luminescence dosimeters (OSLDs) on the patient for each treatment field to measure the entrance dose along the central axis and directly behind the LVAD block. In addition, OSLDs were placed on the inside the box with the controller at distances of 2cm, 8.5cm, and 14cm from the field edge, as shown in Figure 1C. In the figure, the OSLDs are placed on the outside of the box for ease of visualization. The OSLDs were not placed directly on the controller to minimize the handling of the controller and to help expedite the treatment process. Before, during, and after each treatment, the LVAD was interrogated by the cardiology team to monitor the operational parameters of the LVAD. Before, during, and after each treatment, the LVAD was interrogated by the cardiology team to monitor the operational parameters of the LVAD.

Dose Estimation

In addition to the *in vivo* measurements taken during treatment, a series of phantom-based measurements were acquired to estimate the dose more accurately to the LVAD at depth. First, ion chamber measurements in solid water were made to estimate the depth dose behind the LVAD block. An Exradin A12 ion chamber (Standard Imaging, Middleton, WI), with a radius of 0.61 was used for all measurements. The overall size of the solid water phantom was kept constant at 30x30cm^2 and a 24cm thickness. The thickness of the phantom was chosen to match the patient thickness, while the height and width were limited by the size of the solid water available. However, the size was deemed sufficiently large to account for scatter. The phantom was placed 15cm from the spoiler, centered behind the LVAD block location. To acquire a depth dose curve, ion chamber measurements were taken at depths of 1, 2, 3, 4, 6, 9, 12, and 15cm. The effective point of measurement for each of these points was shifted upstream by 0.6 multiplied by the chamber radius upstream, as recommended for cylindrical ion chamber dosimetry[23,24]. These measurements were first taken with the LVAD block placed on the spoiler identical to the treatment setup and the process was repeated with no LVAD block in place. The ratios of these two measurements determined a depth-dependent transmission factor of the LVAD block. To estimate the transmission factor at the surface, an OSLD was placed on the surface of the phantom to measure the dose with and without the LVAD block present. The final dose

estimate to the LVAD motor was based on CT imaging taken subsequently to the TBI treatment. This imaging was used to ascertain the depth of the LVAD motor from the AP and PA directions. From this, the dose to the motor was estimated.

Results

The imaging from the AP and PA simulation and treatment of the patient's chest can be seen in Figure 2. The treatment images include the LVAD blocks. Daily interrogation of the LVAD showed no transient effects during or immediately after radiation. A 15-month follow up reported no ill adverse effects from his TBI conditioning regimen from a cardiac perspective. In fact, the ejection fraction had recovered to 65%, and LVAD team is considering removal and disconnection of LVAD. It appears the risk of damage or injury to the LVAD device, and heart from the neutron contamination or radiation exposure were well reduced. As shown in Table 1, the *in vivo* OSLD measurements showed good agreement between the expected dose of 100cGy and measured dose to the central axis. The AP and PA doses were 103.45 and 102.20cGy, respectively. The OSLDs behind the LVAD block measured 66.49 and 73.61cGy for the same treatment fields. This equates to an average surface dose of 70.05cGy behind the block and a relative transmission factor of 68.1%.

Figure 3 shows the amount of radiation to the controller box and the percentage of the prescribed dose to the central axis, excluding imaging dose. In this region, the out-of-field dose dropped perfectly linearly ($R^2 = 1.000$), ranging from 33.83% (135.30cGy) to 22.87% (91.46cGy) at 2cm and 14.5cm, respectively. Extrapolating the results, the dose at the field edge is estimated to be 35.6% of the prescription (142.5cGy). The dose decreased away from the field edge at 0.91% (3.65cGy) per centimeter. Based on the location of the controller, average dose to the controller is estimated to be 27.5% (110cGy) for the course of the entire treatment.

The result of the transmission factor measurements can be seen in Figure 4. The OSLD based transmission factor at the surface is 67.9%. This agrees very well with the *in vivo* measurements taken. Below the surface, the relative transmission drops until leveling out around 30% at a depth around three centimeters. Starting at a depth of eight centimeters, the dose ratio slowly increased, reaching 31% at a depth of 15cm. The higher values in the region upstream of 3cm can be attributed to a couple factors: in-scatter from the beam spoiler and secondary particles from the LVAD block. The slight increase at the distal edge of the measurements is likely a result of backscatter from the wall beyond the phantom setup and in-scatter from other surfaces in the treatment room. Beam hardening beyond the block may also have contributed to this increase.

The chest CT of the treated patient was used to localize the LVAD motor within the patient. Based on this imaging, the motor, including the housing, was estimated to have a width of 5.7 cm. From the AP direction the motor had a depth ranging from 6.3 to 12.0 cm. From the PA direction, the depth was 7.1 to 12.8 cm. These values fall within the flat region of Figure 4, where the LVAD block transmission was measured around 30%. Based on the estimated total of 200cGy delivered by each field, the final estimated dose to the LVAD motor is 120cGy. However, this estimate has some caveats, was noted in the Discussion section.

Discussion

Based on the measurements acquired, much of the LVAD pump within the patient is estimated to have received around 120cGy. However, a couple factors complicate this estimate. The high-Z titanium shell of the LVAD pump causes attenuation and backscatter. The amount of dose penetrating the titanium to the distal end of the pump itself is likely less than the estimated 30%. However, the dose deposition to the proximal region would have been slightly elevated. These elements would slightly offset, the extent of which is challenging to determine.

Multiple case studies have reported on patients with LVADs receiving external beam radiation[6-15]. All these studies looked at directed radiation, with none involving a patient receiving TBI or LVAD controller dose. These studies looked at multiple generations of devices as new models are commonly being released[19,24]. The case studies suggest a dose tolerance of as much as 7500 cGy[11]. However, one case study identified a patient who received stereotactic body radiation therapy to the lung who later had very significant ventricular

tachycardia burden following treatment which was not accurately recorded by their device[12]. This failure may be a result of radiation damage. Data around other implanted cardiac devices, defibrillators and pacemakers, has shown a large degree of variability in dose sensitivity in these devices[26]. This is likely the case with LVADs, as well.

Most of the studies on LVAD radiation sensitivity have been limited to treatments using low energy photons (<10 MV). X-ray treatments produce neutrons above when photon energies exceed 10 MV, which is associated with malfunctions of contemporary implantable cardiac devices[23]. It is reasonable to assume a similar correlation with LVADs. Gossman et al found that LVADs (n = 2) did not have any changes in pump operation during radiation with 18 MV X-rays dosed 64-75 Gy[14]. More studies are required to fully determine the effect of neutrons on these devices.

We can be optimistic for this patient's future, although the cardiovascular disease in stem cell transplant survivors remains a concern[27].

Conclusion

This case documents the total body irradiation administered to a patient with a HeartMate 3 LVAD and concomitant cancer. Despite direct radiation to the patient's LVAD motor and scatter radiation to the controller, no inappropriate device function was found during device interrogations performed throughout treatment or within 6 months following treatment. The current literature on the effects of radiation on LVADs is limited. As an increasing number of cardiac device-dependent patients will need cancer treatment, it is imperative to understand the best treatment approaches that can be safely offered to this unique population. Further research to address the safety of radiation therapy in patients with LVADs devices is needed.

Patient Consent

Written informed consent was obtained from the patient to publish this report in accordance with the journal's patient consent policy.

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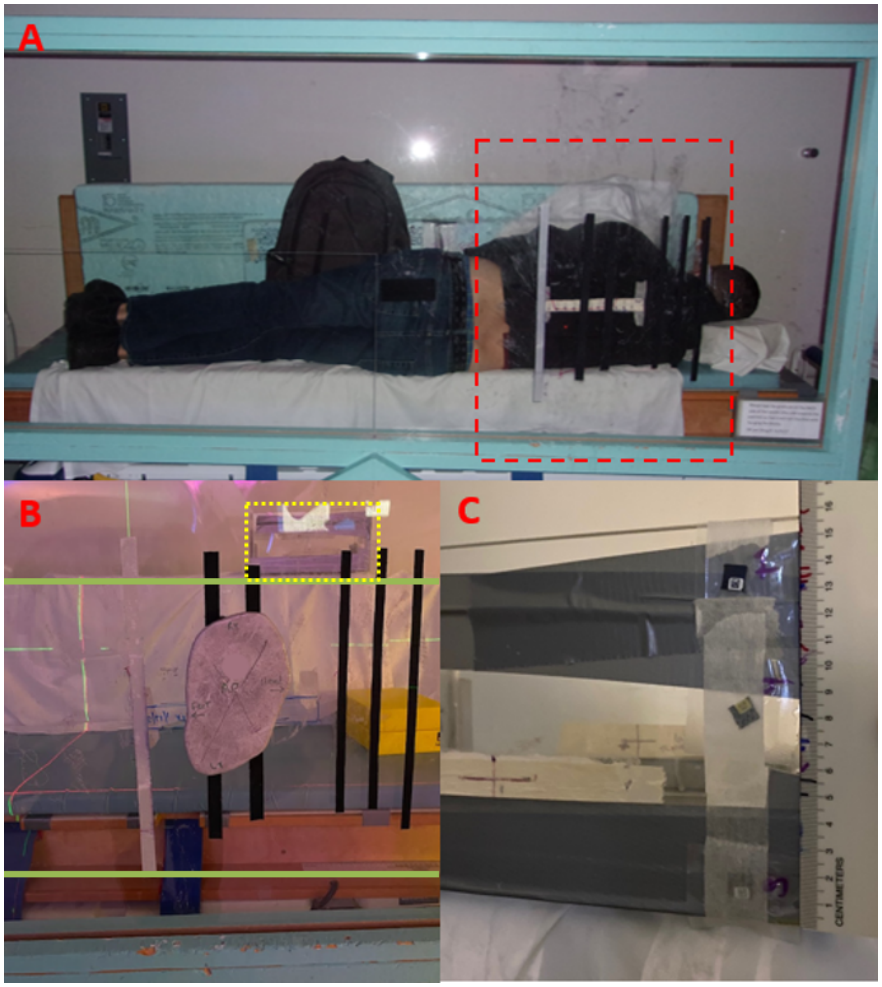

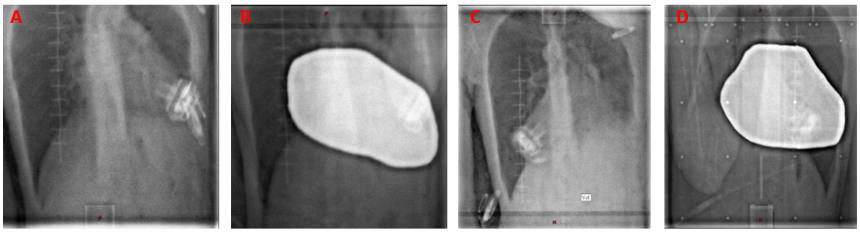

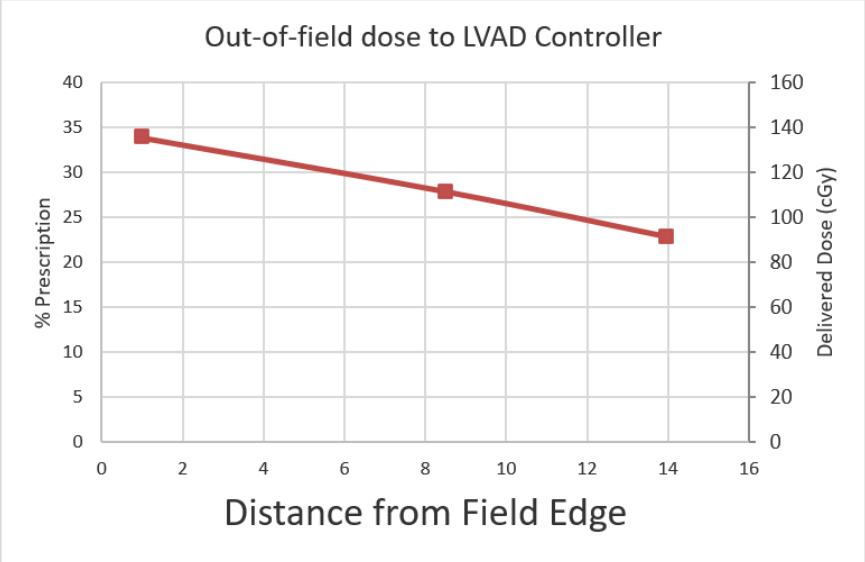

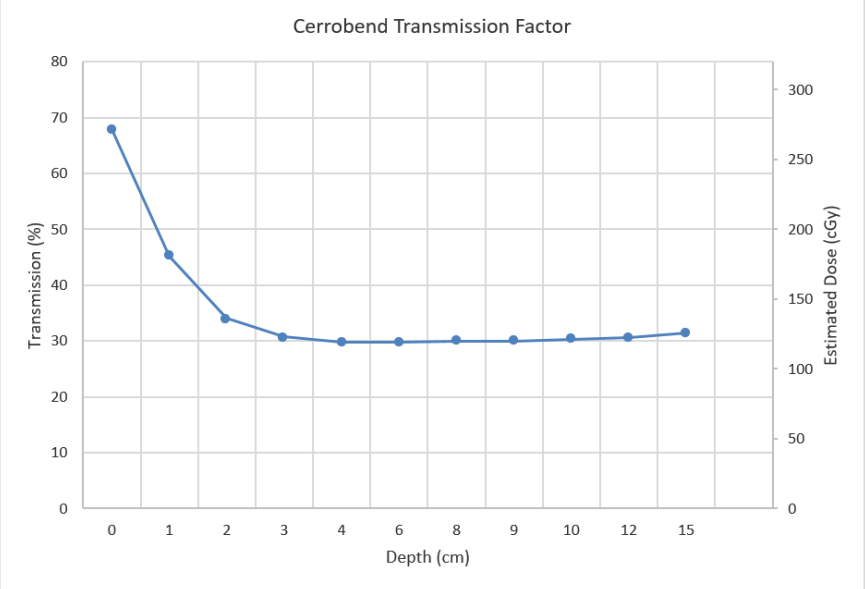

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