Evaluation of a Ventricular Assist Device System: Stability in a Proton Beam Therapy

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Inadequate research exists regarding testing of a ventricular assist device (VAD) for susceptibility to radiation damage. Specifically, minimal data are available to radiation oncologists prescribing treatment plans for patients with an implanted VAD. As the number of implanted devices increases, patients requiring radiation at tissue sites near or at the device will increase. The purpose of this study is to provide the first analysis of radiation effects of proton beams on VADs. Five left VAD (LVAD) pumps (HeartWare Inc., Miami Lakes, FL) were exposed to proton beam radiation at a calibrated dose rate of 5 Gy/min up to a cumulative dose of 70 Gy. The HeartWare LVAD pump recorded parameters including power (W), speed (revolutions/min), and estimated flow (L/min). Analysis of collected data after each irradiation found no deviation in pump parameters from baseline values. The HeartWare LVAD pump exhibited no change in device function when directly irradiated by a high energy proton beam. Secondary neutron fluence created in the proton beam during irradiation had no effect on external components including the system controller and batteries powering the HeartWare LVAD. *ASAIO Journal* 2012;58:597–600.

Key Words: left ventricular assist device, HeartWare left ventricular assist device, radiation, ventricular assist device, proton beam treatment

The HeartWare Inc. pump has no electronics in it and contains only one moving part. The moving impeller is hydrodynamically suspended inside through a combination of passive magnets. When the impeller rotates, blades force the blood to flow in the area of the heart requiring assistance. Significant improvements in design functionality and miniaturization of mechanical circulatory support systems, including the left ventricular assist device (LVAD), have improved morbidity, mortality, and the quality of life for patients with heart failure.[1–3] Approximately, 15–20% of patients with lung cancer have tumors that can be treated with surgery combined with other therapies such as radiation. Another 30–50% of patients with lung cancer have locally advanced tumors that require a combined treatment regimen that includes radiation therapy. Because of the proximity of the lungs to several critical organs in the body, it is challenging to deliver an adequate dose of radiation to a cancerous tumor while sparing nearby normal tissues. Proton beam radiation therapy provides an advantage for many patients with lung cancer due to unique beam characteristics. The growing awareness and availability of clinical high energy proton beams are changing the radiation treatment paradigm.

As the number of patients receiving VAD implantation expands with improved outcomes and quality of life enhancement, it is important to ensure reliable device functionality when exposed to this cancer therapy. Task group no. 34 of the American Association of Physicists in Medicine referenced the significance of radiation damage information to pacemakers.[4] More recent studies for modern devices are now found in literature.[5,6] Significant improvements in the technology of cardiac apparatus with respect to radiation tolerance have been addressed by various research groups.[7–11] Still, most literature addresses mainly x-ray beam radiation, not proton beams, and devices such as the VAD are not designed with radiation hardening in mind. Previous work from some of the investigators concluded no interaction exists between a VAD and medical x-ray particle accelerator.[12] As of the submission date of this article, there is no research published on the effect of proton beam damage to cardiac devices, let alone for a VAD.

Here we report the findings of an *in vitro* study completed to determine any changes in device functionality of an LVAD pump (HeartWare Inc., Miami Lakes, FL) when directly irradiated by high energy therapeutic proton beams used for the treatment of cancer.[13–15] Results from this testing will assist radiation oncologists and medical physicists in the understanding of any known sensitivities the HeartWare LVAD has to incident particle radiation. The HeartWare LVAD pump is a continuous flow VAD implanted in patients to provide assistance to heart failure symptoms *via* circulatory support. The pump is directly inserted into the patient's failing ventricle in the pericardial space and is driven by a patient-worn controller and power source (ambulatory battery sources or alternating

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current/direct current [DC] power) as part of the HeartWare Ventricular Assist System.[16] The HeartWare LVAD is currently approved for use outside the United States and has completed clinical trial enrollment of the Food and Drug Administration and is awaiting approval for sale inside the United States.

Materials and Methods

A total of five HeartWare VADs were evaluated in this study. Each Heart LVAD pump was connected to the system controller and powered by two DC batteries. The pump was programmed to operate under typical patient conditions and with a speed of 2,400 revolutions/min (RPM) and flow range of 3–6 L/min. Pump parameters including power, speed, and estimated volumetric flow rate were collected and analyzed with a custom clinical data acquisition system (CDAS) at a frequency of 50 Hz over the entire study period. Radiation testing was conducted at the Indiana University Health Proton Therapy Center (Bloomington, IN). The proton beam is produced from a cyclotron designed by the Indiana University with a treatment gantry manufactured by IBA Dosimetry GmbH (Schwarzenbruck, Germany).

A high energy proton beam was chosen for delivery, 150 MeV (16 cm range in water), along with the highest dose rate achiev-for the day, 5 Gy/min under calibration conditions.1 (Note: The Gray [Gy] is the International System of Units standard unit for absorbed dose, defined as the absorption of 1 J of ionizing radiation by 1 kg of matter [i.e., human tissue or water]. It is equivalent to 100 cGy or 100 rads. For x-rays and gamma rays, the Gy value is the same as for the Sievert [Sv] dose unit. For protons, 1 Sievert is 2 Gy because of greater impact from protons.) Probeams have a well-known, distinctly sharp Bragg peak in their depth-dose curve that drops dramatically from 100% to 0% in just 0.2 cm at the energy range of 16 cm (for 150 MeV protons). To deliver a uniform radiation dose to the HeartWare LVAD, a spread-out Bragg peak (SOBP) was achieved using a propeller wheel modulator such that the dose is uniform (± 2%) over a selected distance in depth. In our experiment, the R90 of the SOBP was roughly 10 cm from proximal to distal position.17 The uniform dose width of the proton beam profile spreads from 6 to 16 cm with an 11 cm nominal center. The SOBP provides a uniform dose delivery to the HeartWare LVAD as seen in **Figure 1**. The reference condition where dose is calibrated to be within ± 2% for 100 MU/Gy (monitor units) is defined by a 10 cm diameter beam aperture, range 16 cm, SOBP 10 cm, and source position at 250 cm up-stream from the isocenter.

The HeartWare LVAD was mounted inside an IBA Dosimetry GmbH model Blue Phantom water tank and aligned using laser guidance inside the treatment vault. A clamp ensured a rigid position for the pump resulting in minimal mechanical vibration with reproducible orientation. Experimental setup is depicted in **Figure 2**. For a 10 cm circular beam and a 5 cm air gap between the aperture and phantom surface, the resulting output is measured to be 10^{-2} Gy/MU as calibrated according to the International Atomic Energy Agency Technical Reports Series 398 code of practice.[18] Clinically relevant maximum doses for patients with lung cancer is nominally 70 Gy.[14–16] To achieve this dose, the machine was programmed for 7,000 MU. With a dose rate of 500 MU/min, irradiation was continually delivered for 14.0 min for each device. Statistical analysis was performed on the collected data from CDAS using a

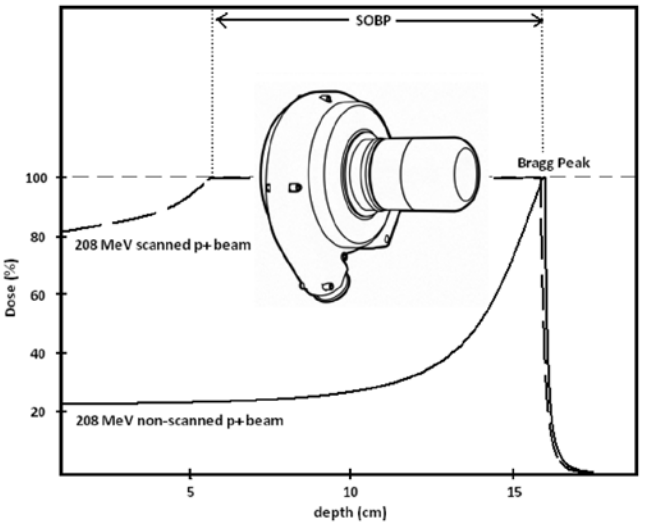

Figure 1. Experimental setup showing location of Heartware left ventricular assist device in the middle of the spread-out Bragg peak (SOBP).

custom LabVIEW (National Instruments, Austin, TX). A paired Student's t-test was used to compare baseline pump parameter data with data taken during radiation treatment. The central axis of the beam was aimed specifically at the point of connection between the pump and driveline wires, as done in prior x-ray testing.[13] The pump was submerged in the water tank to a depth of 14 cm. Early in testing, random drops in flow were observed even when no radiation was applied. Inspection of the experimental setup found debris in the water tank being pulled into the pump and therefore affecting pump power and speed. To eliminate these occurrences, clean water in a closed-loop system was constructed (**Figure 2**). The *in vitro* flow loop contained Tygon PVC tubing connected fore and aft to a 4,700 cm^3 cylindrical plastic canister for water recirculation. With clean water in the loop only, baseline data were constant throughout each experiment. A single 270° lateral proton beam was prescribed. With the beam incident through the side of the tank, the resulting water equivalent depth through the side window to the nominal center of the device is 11 cm as stated above. An air gap of 5 cm was set between the gantry beam aperture and the tank side.

Results

The study revealed no real-time operational changes in the HeartWare LVAD pump for cumulative doses up to 70 Gy from the proton beam. Insignificant change in pump power, speed, or flow during irradiation was documented. Minimal fluctuations were attributed to mechanical vibration and were negligible. The specific data measured for each HeartWare LVAD pump delivery are provided in **Table 1**.

Changes in power were less than 0.05 W indicating normal device operation during the course of study. There was no significant difference between the baseline pump parameter data and the data taken during irradiation as shown in **Table 2**.

No change in appearance or discoloration was observed in any of the device drivelines. The system controller log files were

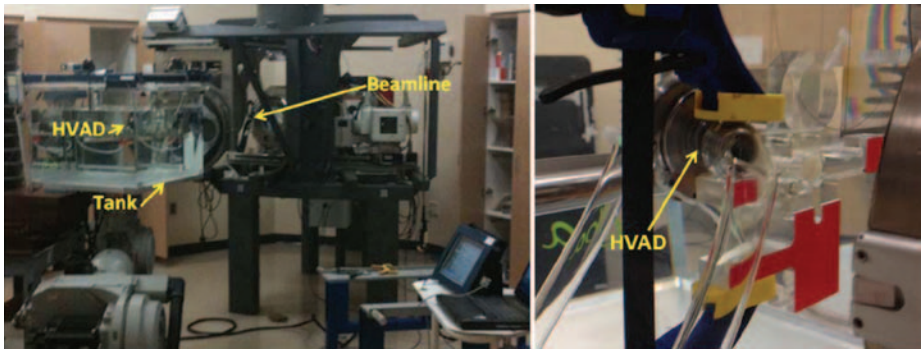

Figure 2. Left: Experimental setup including beamline. Right: Aperture focused on the mounted HeartWare left ventricular assist device (LVAD) positioned in tank. HVAD, HeartWare LVAD.

Table 1. Heartware LVAD Pump Parameters During Stability Testing for Baseline and Treatment Conditions

HeartWare LVAD	Baseline Pump Parameters			Treatment Pump Parameters		
	Power (W)	Estimated Flow (L/min)	Speed (RPM)	Power (W)	Estimated Flow (L/min)	Speed (RPM)
1	3.2±0.1	5.4±0.1	2,400±8	3.2±0.1	5.3±0.1	2,400±8
2	3.0±0.04	4.5±0.1	2,400±6	3.0±0.04	4.5±0.1	2,400±6
3	2.9±0.05	4.0±0.1	2,400±7	2.9±0.04	4.0±0.1	2,400±6
4	2.9±0.04	4.2±0.1	2,400±7	2.9±0.04	4.3±0.1	2,400±7
5	2.9±0.04	3.9±0.1	2,400±7	2.8±0.04	3.8±0.1	2,400±6

LVAD, left ventricular assist device; RPM, revolutions/min.

Table 2. Average Pump Parameter Data and *p* Values for the Baseline and Treatment Conditions

Average	Baseline	Treatment	*p* Value
Power (W)	3.0±0.05	3.0±0.05	0.187
Flow (L/min)	4.4±0.1	4.4±0.1	0.311
Speed (RPM)	2,400±7	2,400±6	0.190

RPM, revolutions/min.

reviewed after each irradiation. These files revealed no alarms or events triggered during device operation. The log files also provided details on the discharge rate for the two batteries used to power the pump. The measured discharge rate was linear with no abnormalities during irradiation for all five devices.

Discussion

The HeartWare LVAD pump was the only component of the device system in the path of the proton beam in the current study. It does not contain sensitive electronics that may suffer severe radiation damage as seen in some implantable pacemaker and cardioverter-defibrillator models.[19,20] It is constructed of a hybrid titanium-ceramic assembly with the impeller containing large rare-earth motor magnets, driven by electromagnetic force.[16] However, the HeartWare LVAD pump has a microprocessor-based controller worn by the patient and connected *via* a percutaneous driveline, which operates the pump, manages power sources, monitors pump function, provides diagnostic information, and stores pump parameter data.[16] In a typical treatment procedure for a patient, the controller is outside the direct beam, as it can be laid on the end of the treatment table. Still, high energy therapeutic proton beams have been proven to cause knockout neutrons that can scatter anywhere, including at the end of the treatment table. With this proton beam energy, phantom geometry, and aperture chosen for irradiation, the neutron fluence has been published as 0.97 mSv/Gy.[21,22] This is roughly 1/1,000th of intensity of the proton beam. This represents a second concern for radiation effects, along with the primary concern over electromagnetic interference from the 150 MeV, positively charged proton beam. If interference of device function is observed in a clinical setting from radiation treatments, the system controller may be replaced. This interchangeability of the system controller provides an added factor of safety to the procedure.

Limitations of this study include the use of estimated flow instead of directly measuring the flow rate, although measurement of relative changes in device function and performance was the focus of this study. No significant differences in pump parameters were measured between baseline and treatment conditions. Only one speed was considered as the study design was limited in amount of time for testing. The 2,400 RPM speed was considered sufficient for measuring relative changes in pump operation and is a common speed used in patient operation.

Still, without such testing, nothing could be reported to ensure a complete understanding of radiation effects on the HeartWare LVAD pump and controller to proton bombardment or secondary neutron irradiation. For an outpatient, battery operation would most likely be used. It is possible that proton or neutron radiation can cause battery depletion, as seen during experimental testing of implantable cardiac pacemakers and implantable cardioverter-defibrillators,[11,16] although no abnormalities were measured in depletion rates for this testing.[19,20]

Conclusions

The incidence of VAD patients with lung, mediastinum, and cardiac cancer undergoing proton therapy will increase with

further adoption of this technology in the near future. To mimic a worst-case proton treatment scenario for lung cancer patients, five HeartWare LVADs were directly irradiated to a dose of 70 Gy under a high fluence of 150 MeV (16 cm range in water) protons. For all five devices, identical results are reported. No noted effects were seen for pump parameters including pump power, estimated flow, and speed. No qualitative changes were observed in the function or appearance of the pump, driveline, batteries, and system controller. It is important that medical devices are fully evaluated for susceptibility to damage, malfunction, or failure. Part of that consideration must be directed for patients who may suffer from cancer and then in need of radiation therapy, whether they are diagnosed with cancer before implant or afterward. Particularly, these data are clinically relevant to patients with lung cancer, where the doses are typically high and the pump is in close proximity to the lung.

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