Optimizing heart dose reduction for deep inspiration left breast radiotherapy

Ronald James Harder

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OPTIMIZING HEART DOSE REDUCTION FOR DEEP INSPIRATION

LEFT BREAST RADIOTHERAPY

by

Ronald James Harder

Bachelor of Arts
San Francisco State University
1999

A thesis submitted in partial fulfillment of
the requirements for the

Master of Science in Health Physics
Department of Health Physics and Diagnostic Sciences
School of Allied Health Sciences

Graduate College
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Ronald James Harder

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December 2011
ABSTRACT

Optimizing Heart Dose Reduction for Left Breast

Deep Inspiration Radiotherapy

by

Ronald James Harder

Dr. Phillip Patton, Advisory Committee Chair
Professor of Health Physics & Diagnostic Sciences
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Multiple studies have shown that an increased risk of late injury cardiac abnormalities including congestive heart failure (CHF), ischemia, and coronary artery disease (CAD) can be associated with common left breast radiation therapy (RT) techniques. Many radiation therapy clinics have adopted the Deep Inspiration Breath Hold (DIBH) technique for the treatment of the left breast with external beam therapy based on studies showing a decrease in the dose received by the heart. A common technology used to monitor inhalation during DIBH is the Real-Time Position Management (RPM) system (Varian Medical Systems, Palo Alto, CA). This study analyzes if there is an optimal setup protocol for the use of the RPM system in order to minimize heart dose during DIBH RT of the left breast.
ACKNOWLEDGEMENTS

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CHAPTER 1
INTRODUCTION

Breast Cancer Treatment and Heart Complications

According to the National Cancer Institute the estimated number of new breast cancer cases in the United States in 2011 will be 230,480 for females and 2,140 for males. The proportion of breast cancer patients treated with Radiation Therapy (RT) has increased substantially as it is an effective treatment which reduces the risk of both local cancer recurrence and breast cancer death.\textsuperscript{1,2} However, multiple studies have shown that an increased risk of late injury cardiac abnormalities including congestive heart failure (CHF), ischemia, and coronary artery disease (CAD) can be associated with common left breast RT techniques.\textsuperscript{3-5} Since the correlation of cardiac abnormalities with left breast RT was discovered, multiple techniques have been developed to minimize dose to the heart.\textsuperscript{1,6} This study aims to optimize one of these techniques to further reduce dose to the heart.

External Beam Radiation Therapy for Breast

The goal of radiation therapy is to deliver a very accurate dose of radiation to a well-defined target volume with minimal damage to surrounding healthy tissues, resulting in the eradication of the disease, the prolongation of life, and or the improvement in the quality of life.\textsuperscript{7} External beam RT uses high energy x-rays to kill cancer cells by damaging their DNA. If the DNA is damaged beyond repair the cancer cells will die. Healthy cells will also be damaged during RT, however,
they are more adept at repairing sublethal damage than cancer cells. It is primarily for this reason that the total dose delivered during RT is fractionated. Dividing the total dose delivered to the tumor into a number of fractions, typically delivered in one day intervals, spares normal tissues because of the repair of sublethal damage between dose fractions and cellular repopulation. The typical dose delivered to breast patients is 1.8-2.0 Gray (Gy) per fraction until a total dose ranging from 46-50 Gy is delivered. Dose \( D \) is defined as:

\[
D = \frac{d\bar{\epsilon}}{dm}
\]

where \( d\bar{\epsilon} \) stands for the mean energy imparted by ionizing radiation to material of mass \( dm \). Dose is most commonly measured in units of Gy. Upon diagnosis of breast cancer a patient could be presented with several treatment options based on several factors such as the stage of the cancer, age, and overall health. Breast conservation therapy, where the patient receives RT after the tumor is first surgically removed, has become the preferred treatment for the majority of breast cancer patients with Stage 0, I, or II breast cancer. If RT is included in the modality of treatment a computed tomography (CT) scan of the patient is acquired. The CT scan is then entered into a treatment planning computer (TPC) where important structures relevant to the case are typically contoured by a radiation oncologist and an optimized treatment plan is created for the patient (Fig. 1). The treatment plan parameters are entered into a treatment machine; typically capable of rotating 360 degrees around the patient as they lie on a patient support table, allowing a beam of high energy x-rays to
enter the patient from multiple angles. The most common type of breast cancer RT involves the use of tangential fields (Fig. 2).

Figure 1: Example of a typical tangential field treatment plan created for this study. Figures a), c), and d) display the transversal, coronal and sagittal planes of the treatment plan respectively while figure b) displays a 3D model of the treatment fields in relation to the contoured structure in the plan.
Figure 2: Treatment Machine, with red lines simulating the radiation beam for tangential breast treatment: a) Medial tangential field, b) Lateral tangential field.

The size and shape of the radiation beam is adjusted by the treatment unit to fit the target of interest based on the treatment plan. The patient lies in the supine position with the ipsilateral arm of the breast being treated placed above the head. Two tangential fields are aligned to the breast with the edges of all the fields aligned with each other. Often, a portion of the heart, the majority of which is typically the left ventricle, will reside within the treatment fields (Fig. 1a). Respiration-induced heart motion can result in substantial intrafractional dosimetric variation of the heart for a subset of left-sided breast patients.11 Studies have shown that with traditional tangential radiation therapy for breast or chest wall the whole heart dose can vary from 1.4-4.4 Gy and the Left Anterior Descending Coronary Artery (LADCA) dose can vary between 2.4-21.2 Gy for
left side treatments. The LADCA is a relatively large artery that swings around the pulmonary trunk and runs along the anterior interventricular sulcus providing blood to the left and right ventricles and the interventricular septum. A Swedish study in 1998 performed a comparison of cardiac abnormalities in 960 patients treated from 1971-1976. Of the 960 patients, 316 were treated with preoperative RT (45Gy, Cobalt-60), 320 postoperative RT (45Gy, Electrons), and 321 surgery only (Control Group). An increased cardiac mortality was only observed for patients treated for left breast cancer with tangential Cobalt-60 fields. There was an increased incidence of ischemic heart disease which was speculated to have resulted from damage to the microvasculature. A US study in 2006 evaluated 62 patients treated for left breast with tangential field RT between 1977 and 1995. At a median of 12 years post-RT, the incidence of cardiac diagnostic test abnormalities among these patients was significantly higher than the predicted incidence of cardiovascular disease in the patient population, 6/62 (9%) predicted vs. 24/62 (39%) observed. Since the correlation of cardiac abnormalities with left breast RT, multiple techniques have been developed to minimized dose to the heart, one such technique is Deep Inspiration Breath Hold.

Deep Inspiration Breath Hold

Many radiation therapy clinics have adopted the Deep Inspiration Breath Hold (DIBH) technique for the treatment of left breast cancer with external beam therapy based on studies showing a decrease in the dose received by the heart. The patient is required to hold their breath at deep inhalation while the treatment beam is enabled. DIBH treatments for breast and chest wall carry two
advantages. The first advantage is that motion caused by respiration can be minimized, allowing for the reduction of the internal margin (IM) which is placed around the tumor to compensate for intrafraction motion during treatment. The second advantage is that the target to organ at risk (OAR) distance can be increased, thereby reducing dose to the OAR. The DIBH technique has been shown to decrease the median heart volume receiving >50% of the prescription dose from 8% to 1% and median left anterior descending coronary artery volume from 54% to 5%. A strong positive correlation has been shown between the Maximum Heart Distance (MHD) and the mean heart dose where 81% of the variability in mean heart dose is accounted for by the MHD. MHD is defined as the maximum distance between the anterior cardiac contour and the posterior tangential field edge as displayed on a beam's eye view of a treatment field (Fig. 3). Mean heart dose predictions based on MHD have been shown to be within 1.8%. The DIBH technique is typically achieved by monitoring or controlling patient inhalation level with a variety of different technologies including Automatic Breath Control (ABC) devices, 3D surface mapping systems, magnetic sensors, and several others. A common technology used to monitor inhalation during DIBH is the Real-Time Position Management (RPM) system (Varian Medical Systems, Palo Alto, CA). The RPM system uses a small plastic block with retro-reflective infrared reflectors which is typically placed on the patient’s abdomen between the umbilicus and xiphoid process to maximize anterior-posterior (AP) motion due to respiration. Abdominal placement of the reflector block is the recommended position by the American Association of Physicists
Figure 3: Maximum Heart Distance (MHD) which is defined as the maximum distance between the anterior cardiac contour and the posterior tangential field edge as displayed on a beam’s eye view of a treatment field.

in Medicine Task Group 76 report on the management of respiratory motion in radiation oncology. The reflector block is placed in the same location for planning CT acquisition and treatment sessions, typically through measurement from the umbilicus or the use of skin marks, as accurate placement is critical for reproducible treatments. A charged-coupled device (CCD) camera fitted with infrared emitting diodes is used to track the position of the reflector block. The video signal is sent to a dedicated Windows based PC where the software
displays a sinusoidal representation of the reflector block motion as a function of time (Fig. 4).

Figure 4: RPM System: a) CCD Camera, b) Reflector Block, c) Typical Block Placement, d) RPM Software Application.

Research Goal

The main goal of this study is to determine the optimal position of the RPM reflector block for left breast RT patients using the DIBH technique to decrease heart dose, specifically to the left ventricle. I hypothesized that the position of the RPM reflector block can play a critical role in determining the MHD, and that placement on the xiphoid process will minimize MHD in order to minimize mean heart dose and mean left ventricle dose. I hypothesized that abdominal placement of the reflector block influences patients into abdominal breathing
where the lungs expand inferiorly with the diaphragm with varying degrees of thoracic expansion. The most important muscle of inhalation is the diaphragm. As the diaphragm contracts, it forces the abdomen inferiorly and anteriorly when it descends, increasing the superior-inferior (SI) dimension of the chest cavity.19 A recent breathing study shows that during quiet breathing while in the supine position, movement of the abdomen was approximately double that of the upper and lower thorax. Deep breathing showed similar results for men, while in women, upper thoracic movement was slightly larger than abdominal movement.20 By placing the reflector block on the xiphoid process or slightly superior I hoped to show an increase in thoracic expansion leading to reduced heart dose by minimizing the MHD. In addition, I hypothesized that abdominal compression applied by a neoprene-velcro belt would further increase thoracic expansion leading to a further reduction of dose to the heart.
CHAPTER 2

METHODS AND MATERIALS

RPM System Setup

A RPM system was setup in the MRI control area. The CCD camera with infrared emitting diodes was placed against the viewing window in line with the MRI scanner bore at a distance of approximately 4 meters from the isocenter of the scanner (Fig. 5). A RPM reflector block was placed in the bore of the scanner to verify the alignment of the camera and that the system was tracking properly. A large LCD monitor, connected to the RPM computer, was placed next to the camera in the viewing window for visual coaching of each volunteer. The RPM system provides a means of visual feedback coaching to the patient to help facilitate breathing reproducibility. This is typically setup in the form of a head mounted display (video goggles) placed on the patient which cannot be used on MRI scanners. The visual coaching monitor displays the limit of inhalation set during the evaluation phase of a patient’s DIBH capabilities (Fig. 6).

Figure 5: RPM system setup in MRI control area
Figure 6: a) Breathing trace produced by tracking the RPM reflector block. b) DIBH thresholds established during patient assessment. c) The blue area correlates to the DIBH thresholds. The green bar correlates to the position of the reflector block on the patient. The red outline represents the display shown on the visual coaching monitor. During normal breathing the green bar would move up and down within the region defined by the orange dashed lines.

Volunteer Coaching

Twelve volunteers (9 female, 3 male) ranging in age from 19-55 years, mean age of 39, agreed to take part in this IRB approved study. Each volunteer
signed an informed consent form outlining the purpose of the study, the procedures that would be performed, the benefits of participation, and risks of participation. Volunteers were not compensated monetarily for their participation. Volunteers were not given any information regarding the study prior to arriving on site the day of participation. Each volunteer was provided with approximately 10-15 minutes of instruction prior to being scanned where they were informed of the purpose of the reflector block, given an explanation of the visual coaching monitor, shown the position of the xiphoid, and allowed to ask any questions. Volunteers were instructed to remove any metal objects from their body and female volunteers were instructed to wear bras without metal clips (sports bras were recommended). Volunteers were setup in the supine position with both arms lying by their sides. The typical arm position for left side breast treatment is to have the ipsilateral arm placed above the head, which was not feasible as a mirror residing in a MRI head coil was used to allow volunteers to view the visual coaching monitor setup in the control area window. The space between the head coil and MRI bore was not adequate to place the left arm above the head. The RPM reflector block was placed on the abdomen, between the xiphoid and umbilicus, prior to the volunteer entering the bore and held in position using medical tape. After the patient was setup in the bore of the MRI it was verified that they could see the visual coaching monitor in the head coil mirror. Volunteers were monitored at all times and further instructions were communicated through the MRI intercom system unless entering the scanner room was required.
MRI Scan Acquisition

Magnetic Resonance Imaging (MRI) was the imaging modality of choice for this study due to the fact that it does not use ionizing radiation for image acquisition. MRI is based on the principle of nuclear magnetic resonance (NMR), specifically, the NMR of hydrogen atoms in the body. When hydrogen atoms are placed in a strong magnetic field ($B_0$) they begin to precess, or wobble, about the axis of $B_0$. The rate at which they precess about the $B_0$ axis is determined by the Larmor equation (Eq. 2):

$$\omega = \gamma B_0$$  \hspace{1cm} \text{Eq. 2}

where $\omega =$ the angular precessional frequency (or Larmor frequency) of hydrogen, $\gamma =$ gyromagnetic ratio of hydrogen (42.6MHz/T), and $B_0 =$ the strength of the magnetic field. The MRI system used in this study has a $B_0$ of 3.0T, therefore the hydrogen atoms in the volunteers had a Larmor frequency of 127.8MHz. If a radio frequency (RF) pulse is applied at this Larmor frequency perpendicular to $B_0$ it will cause the hydrogen atoms to flip at an angle (flip angle) dependent on the strength or duration of the RF signal. If the flip angle is for example 90°, the flipped hydrogen atoms will now all be precessing in phase, 90° from the $B_0$ axis. The time it takes for 63% of these flipped hydrogen atoms to dephase is referred to as "T2 relaxation time" or "transverse relaxation time". The time it takes for 63% of the hydrogen atoms to line up with $B_0$ is referred as "T1 relaxation time" or "longitudinal relaxation time". T2 and T1 will vary in different
tissue types; however T2 is always shorter than T1 for a given tissue. As the hydrogen atoms relax they transmit an RF signal proportional to the hydrogen density, T1, and T2 properties of the tissue. Depending on the timing between RF pulses (TR=Repetition Time) and the time at which the RF signal produced by the relaxing hydrogen atoms is measured (TE=Time of Echo), different signal intensities will be observed for different tissue types. Short TR and TE sequences produce T1 weighted images, and Long TR and TE sequences produce T2 weighted images.

Gradient coils are used in the X, Y, and Z axes to cause an intentional perturbation in B₀, allowing for spatial encoding of received signals to localize them in space. MRI has a variety of complex scanning techniques based on these principals which allow it to display excellent tissue contrast in virtually every part of the body. A total of 48 T1 weighted MRI scans were acquired of the volunteers on a Philips Medical Systems Intera 3.0T MRI scanner using the 3D eTHRIVE breath hold scanning protocol (TR/TE 3.1ms/1.37ms, resolution 0.98x0.98x1.5mm³, 133 slices). This scanning protocol was selected for its fast acquisition time and inherent breath hold setup. Four scans were acquired of each volunteer in the following order: free breathing scan (FB), DIBH scan with the reflector block placed on the abdomen between the xiphoid and the umbilicus (BHA), DIBH scan with the reflector block placed on the xiphoid (BHX), and a DIBH scan with the reflector block placed on the xiphoid with a neoprene-velcro belt wrapped around the abdomen with the compression adjustment determined by the volunteer (BHXB). Volunteers were instructed to adjust the belt so that it
applied constriction but was not uncomfortable. The volunteers remained in the MRI bore for all 4 scans unless they required assistance applying the neoprene belt or were unable to apply it while in the scanner bore. An initial scout acquisition was acquired to adjust the volume of interest before acquiring any study acquisitions. If a volunteer was removed from the scanner bore between scans, typically for adjusting the neoprene-velcro belt, a new scout acquisition was acquired. This was required on approximately half of the volunteers.

Prior to each breath-hold scan the volunteers were instructed to take a deep breath and hold while the RPM visual coaching thresholds were adjusted to the proper amplitude (Fig. 6). Breath-hold thresholds were then verified for reproducibility and comfort by having the volunteers repeat the breath-hold while using the visual coaching monitor to maintain proper inhalation level. This process was repeated for each of the breath-hold scans. Breath-hold scans required a two part acquisition where the volunteers were required to hold their breath for 18-20 seconds for each half of the acquisition. Following the BHA scan the reflector block was moved to the xiphoid for the two remaining scans, BHX and BHXB. Below is a typical example of one of the traces recorded by the RPM software for a breath-hold scan showing that the position of the reflector block during the two part acquisition is approximately the same (Fig. 7). A sagittal slice of the scan acquired with this breathing trace displays excellent agreement of the anterior surface of the patient between the two portions of the acquisition (Fig. 8).
Figure 7: Reflector block trace recorded during DIBH scan

Figure 8: Sagittal plane displaying excellent agreement of the anterior surface of the patient between the two 18-20 second portions of the acquisition (green arrow).
Treatment Planning

Volunteer scans were anonymized and assigned patient IDs of CS1-CS12 prior to being imported into an Eclipse treatment planning computer (Varian Medical Systems, Palo Alto, CA). Each of the scan types was labeled FB (Free Breathing), BHA (Breath-Hold Abdomen), BHX (Breath-Hold Xiphoid), and BHXB (Breath-Hold Xiphoid with Belt). Of the 48 scans acquired, 5 scans were not viable. The entire set of scans for CS12 had to be discarded due to the superior edge of the scan range not including a majority of the heart and the FB scan of CS2 could not be imported into the system for unknown reasons (corrupted data suspected). CS11 scans displayed a large distortion artifact that encompassed the entire inferior thoracic spine (approximately T6 and lower) likely caused by a metal bra clip. This did not impact the measurement of MHD or contouring of the heart and left ventricle, therefore the CS11 results are included in this study.

Once imported into the treatment planning computer (TPC) a structure template created for this study was assigned to the 3D image of each of the scans. The structure template contained non contoured structures of interest labels for this study which include the whole heart (contoured from the base of the heart inferiorly to include the atriums and ventricles), left ventricle, left lung, Planned Target Volume (PTV, in this study the left breast) and the body. In the majority of breath-hold scans the superior and/or inferior border of the left lung was outside of the scan range, thus total left lung volume could not be measured and was not included in this study. The same issue occurred for the left breast of the large breasted volunteers. The ipsilateral arm was removed from the body.
contour to help simulate the proper patient setup for tangential breast treatment.

The Eclipse TPC incorporates a number of automated contouring tools designed to make the contouring process more accurate and efficient. The majority of these tools are designed to work with CT based 3D images and do not function with 3D MRI images. As a result, the majority of contouring had to be performed manually. The use of an image contrast gradient tool allowed for the body and left lung contours to be automatically generated with limited success, both required extensive manual editing. A total of 43 3D images were contoured individually (Fig. 9).

Figure 9: Example of structures contoured on 3D MRI for a Free Breathing Scan: a) displays the list of structures defined for the plan, b), d), and e) display the transversal, coronal, and sagittal planes with the contoured structures, and c) displays a 3D model of the contoured structures.
Tangential field treatment plans were individually created for each of the contoured 3D images. In order for the TPC to calculate dose, a CT number, or Hounsfield Unit (HU) number, had to be assigned to each of the contoured structures. When a CT scan is created, the CT reconstruction algorithm generates CT numbers which are related to linear attenuation coefficients. CT numbers range from -1000 to +3000, where air is -1000, water is 0, and dense bone or areas filled with contrast agents can range up to +3000. The CT number assigned to each pixel of a CT image is calculated using the following equation (Eq. 3):

\[
CT(x, y) = 1000 \frac{\mu(x, y) - \mu_{water}}{\mu_{water}}
\]

Eq. 3

where \(\mu(x, y)\) is the linear attenuation coefficient of the \((x, y)\) pixel and \(\mu_{water}\) is the linear attenuation coefficient of water. CT numbers assigned to the structures in this study were as follows: Whole Heart and Left Ventricle (40), Left Lung (-700), Body (0), PTV (0). All plans were calculated for a total dose of 5040cGy delivered in 180cGy fractions with 6MeV beams. Dose requirements for all plans was to achieve a minimum of 85% and no greater than 110% of the total prescribed dose to 100% of the PTV. Dose Volume Histograms (DVH), which display the volume of a structure versus the dose received, were created for CS1-CS11. Figure 10 displays the DVH for the Left Ventricle (LV) and Whole Heart (WH) volumes corresponding to each of the scan types for CS8. A DVH provides quantitative information regarding how much dose each volume receives and also summarizes the entire dose into a single curve for each
structure of interest. It is therefore a great tool for evaluating a given plan or comparing competing plans. The remaining DVHs are available for review in appendix A.

Figure 10: DVH for CS8 comparing dose to the Left Ventricle (LV) and Whole Heart (WH) for the Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB).
CHAPTER 3

RESULTS

Comparison of MHD for Different Block Positions

The main goal of this study is to identify the optimal positioning of the RPM reflector block for left breast RT patients using the DIBH technique to decrease heart dose. The results of this study show a positive correlation between the placement of the RPM reflector block on the xiphoid process versus abdominal placement for decreasing the MHD. The mean MHD calculated for each of the scan types are: FB =1.0 ± 0.7 cm, BHA=0.1 ± 0.6 cm, BHX= -0.3 ± 0.4 cm, BHXB= -0.4 ± 0.5 cm (Table 1).

Table 1: Maximum Heart Distance (MHD) measurements for the Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations (StdDev) calculated to 1σ.

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<td>CS6</td>
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<td>CS7</td>
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<tr>
<td>CS8</td>
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<td>CS9</td>
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</tr>
<tr>
<td>CS10</td>
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<tr>
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<tr>
<td>StdDev</td>
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</table>
The negative mean MHD results for the BHX and BHXB scans are the outcome of measurements made from the posterior edge of the treatment field to the closest anterior portion of the heart residing outside of the treatment field (Fig. 11). Therefore the BHX and BHXB techniques resulted in greater separation between the left breast and heart when compared to the BHA technique. The BHA technique resulted in 55% of the scans resulting in a negative MHD versus 73% for both the BHX and BHXB techniques. A graphical representation including all scan types is shown below with standard deviations (Fig. 12). All standard deviations displayed in this study are calculated to 1σ. Several examples of MHD measurements are provided in appendix B.

Figure 11: Negative Maximum Heart Distance (MHD) measurement made from the posterior edge of the treatment field to the closest anterior portion of the heart residing outside of the treatment field (green arrow).

Statistical analysis was performed using Analysis of Variance (ANOVA) to determine if there was a statistically significant difference between the three DIBH scan techniques with the pairwise comparisons of each significant relationship presented on each of the following graphs as BHA-BHX, BHA-BHXB,
and BHX-BHXB. A $p$-value of less than 0.05 indicated that there was a statistically significant difference between the scan types.

![Graph showing Mean MHD vs. Scan Type]

Figure 12: Mean Maximum Heart Distance (MHD) for the study group versus scan types: Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations calculated to 1$\sigma$.

Relationship of MHD and Heart Dose

As discussed earlier, it has been shown that there is a direct correlation between the MHD and heart dose. The results of this study corroborate these findings. The scan types displaying the greatest mean dose reduction to both the left ventricle and whole heart were the same which displayed smallest MHD,
BHX and BHXB. The mean left ventricle dose calculated for each of the scan types are: \( FB = 514.6 \pm 393.4 \) cGy, \( BHA = 261.8 \pm 112.5 \) cGy, \( BHX = 199.0 \pm 42.9 \) cGy, \( BHXB = 198.6 \pm 51.2 \) cGy (Table 2). As would be expected, mean dose to the whole heart had very similar results. The mean whole heart dose calculated for each of the scan types are: \( FB = 354.0 \pm 241.5 \) cGy, \( BHA = 191.8 \pm 75.1 \) cGy, \( BHX = 161.1 \pm 31.1 \) cGy, \( BHXB = 155.3 \pm 33.6 \) cGy (Table 3).

Table 2: Left Ventricle (LV) Dose Measurements per Scan Type: Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations (StdDev) calculated to 1\( \sigma \).
Table 3: Whole Heart Dose Measurements per Scan Type: Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations (StdDev) calculated to 1σ.

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</table>

The mean dose to the left ventricle accounted for a mean percentage of 76±3% of the whole heart dose for DIBH techniques. Much of the research referenced in this study refers to the dose received by the LADCA, however, direct results for the LADCA are not reported in this study. Although the general location of the LADCA is well understood, it could not clearly be distinguished on the study scans. I would contend that the dose delivered to the LADCA would follow the same trends as the dose delivered to the left ventricle and the whole heart for the scan types studied. Graphical representations of mean MHD versus mean heart dose for the scan types are displayed on the following page (Figs. 13&14).
Figure 13: Mean Maximum Heart Distance (MHD) vs. Mean Left Ventricle (LV) Dose for the various scan types: Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations calculated to 1σ.
Figure 14: Mean Maximum Heart Distance (MHD) vs. Mean Heart Dose for the various scan types: Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations calculated to 1σ.
CHAPTER 4

DISCUSSION

Upon examination of the acquired data it became evident that three main criteria could be evaluated to relate how the DIBH technique increases the distance between the heart and the chest wall, thereby decreasing the MHD and the dose received by the heart: inferior heart shift, partial lung volume in proximity to the heart, and thoracic expansion. A comparison between all three criteria and dose received by the left ventricle was performed for all scan types. Doses received by the whole heart and left ventricle are comparatively the same, therefore the following discussions focus on the left ventricle which received the greater integral dose of the two and accounted for the majority of dose to the whole heart.

Comparison of Inferior Heart Shift and Heart Dose

The inferior movement of the heart is caused by the diaphragm moving inferiorly during inspiration. The pericardium, the lining of the pericardial cavity which envelopes the heart, has a fibrous attachment to the diaphragm at its inferior portion. During inspiration this fibrous attachment pulls the heart inferiorly with the diaphragm. Measurements of this inferior shift were performed by measuring from the inferior edge of the sternum body to the inferior portion of the left ventricle (Fig 15). Several examples of inferior heart shift measurements are provided in appendix C. This inferior shift of the heart is not expressly mentioned in any of the reference articles related to DIBH with RPM, rather, dose
sparring was related to factors such as “lung inflation” and “chest wall excursion”. Inferior heart shift was therefore not considered prior to beginning this study.

Figure 15: Inferior heart shift measurements of CS6 for the various scan types: a) Free Breathing (FB), and Deep Inspiration Breath-Hold techniques, b) Breath-Hold Abdomen (BHA), c) Breath-Hold Xiphoid (BHX), d) Breath-Hold Xiphoid with Belt (BHXB).

Further research revealed studies describing the superior-inferior (SI) movement of the heart during respiration. This observation does not preclude the notion that “lung inflation” and “chest wall excursion” play a role in reducing heart dose
during DIBH, as they most certainly do. I only wish to point out that a direct correlation between the amount of inferior heart movement and the mean dose received by the left ventricle was observed. The mean inferior heart shift calculated for each of the scan types are: FB = 1.9 ± 1.3 cm, BHA = 4.9 ± 1.2 cm, BHX = 5.3 ± 1.1 cm, BHXB = 5.1 ± 1.0 cm (Table 4).

Table 4: Inferior heart shift measurements per scan type: Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations (StdDev) calculated to 1σ.

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</table>

Only a slight variation is observed between the mean inferior heart shifts of the three DIBH scans. However, when plotted against the mean dose received by the left ventricle, the BHX and BHXB scans resulted in less dose to the left ventricle compared to the BHA scans (Fig. 16). These results indicate that there are other determining factors related to the BHX and BHXB scans which resulted in reduced dose to the heart.
Figure 16: Mean Inferior Heart Shift vs. Mean Left Ventricle Dose for the various scan types: Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations calculated to 1σ.

Comparison of Partial Lung Volumes and Heart Dose

Partial lung volume for all scan types was calculated by defining the superior and inferior borders of the partial lung volume as the distance between superior portion of the T8 vertebral body to the inferior portion of the T10 vertebral body (approximated by choosing the superior vertebral body directly anterior to the xiphoid) (Fig. 17). This resulting volume was located directly
adjacent to the heart on all scans. The mean partial lung volumes calculated for each of the scan types are: FB= 316.8 ± 122.3 cm³, BHA=614.0 ± 132.9 cm³, BHX= 717.1 ± 150.8 cm³, BHXB= 698.3 ± 128.7 cm³ (Table 5).

Figure 17: Partial lung volume measurement: a) green arrows correlate to the superior and inferior borders of the volume measured based on the vertebral bodies, b) green arrows correlate to the superior and inferior borders of the partial lung volume which approximates the superior and inferior borders of the left ventricle.
Table 5: Partial lung volume measurements per scan type: Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations (Std Dev) calculated to 1σ.

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Placement of the RPM reflector block on the xiphoid compared to abdominal placement resulted in a 14% increase in mean partial lung volume in the region of the heart where this effect is most desired, correlating to less dose to the heart (Fig. 18).
Figure 18: Mean Partial Lung Volume vs. Mean Left Ventricle (LV) Dose for the various scan types: Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations calculated to 1σ.
Comparison of Thoracic Expansion and Heart Dose

Thoracic expansion was measured by determining two distances from the inferior-anterior portion of the middle vertebral body (T9) used in the partial lung volume measurements so that the partial lung volume and thoracic expansion measurements were associated (Fig. 19). A vertical measurement was made from this location to the middle of the sternum. A second measurement was made from the same location to the chest wall at a 40 degree angle in reference to the vertical measurement (Figs. 20 & 21). This angle was chosen for the reasons that this measurement approximately bisects the heart on the FB scans and creates a line that is roughly perpendicular to the tangential treatment fields.

Figure 19: Determination of the measurement point for thoracic expansion: a) displays the sagittal determination of the point based on the inferior-anterior portion of T9, b) displays the location of the measurement point in relation to the partial lung volume measurement.
Figure 20: Thoracic expansion measurements for CS8: Free Breathing.
Figure 21: Thoracic expansion measurements for CS8: Breath-Hold Xiphoid.

The mean vertical thoracic expansion measurements calculated for each of the scan types are: FB = 9.8 ± 1.8 cm, BHA = 11.0 ± 2.3 cm, BHX = 11.9 ± 1.6 cm, BHXB = 12.0 ± 1.8 cm (Table 6). The mean angled thoracic expansion measurements calculated for each of the scan types are: FB = 11.4 ± 1.5 cm, BHA = 12.6 ± 1.9 cm, BHX = 13.6 ± 1.3 cm, BHXB = 13.7 ± 1.4 cm (Table 7). Placement of the RPM reflector block on the xiphoid compared with abdominal placement resulted in greater thoracic expansion in both the vertical and angled measurements by approximately one cm in the region of the heart where this effect is most desired, correlating to less dose to the heart (Figs. 22 & 23).
Table 6: Vertical thoracic expansion measurements per scan type: Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations (Std Dev) calculated to 1σ.

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Table 7: Angled thoracic expansion measurements per scan type: Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations (Std Dev) calculated to 1σ.

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Figure 22: Mean Vertical Thoracic Expansion vs. Mean Left Ventricle (LV) Dose for the various scan types: Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations calculated to 1σ.
Figure 23: Mean Angled Thoracic Expansion vs. Mean Left Ventricle (LV) Dose for the various scan types: Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB). Standard deviations calculated to 1σ.
Positioning the RPM reflector block on the xiphoid displayed a 24\% reduction in mean dose to the left ventricle and 16\% reduction to the whole heart versus abdominal positioning (BHX vs. BHA). The BHX scan group also displayed the lowest standard deviation of MHD and dose suggesting that the xiphoid placement of the block would be the best default position for the population. A statistically significant difference ($P<0.05$) was observed between the BHA and BHXB scan types but not between the BHA and BHX scan types when comparing MHD. However, no statistically significant difference ($P>0.05$) was observed between the BHX and BHXB scan types indicating the two techniques are comparable. Dose sparing of the heart through DIBH appears to result largely from a combination of both an inferior heart shift, as the heart moves inferiorly with the diaphragm, and thoracic expansion as lung volume increases. While no statistically significant difference was observed for the inferior heart shift or partial lung volume measurements between the three DIBH scan types, the thoracic expansion measurements displayed a statistically significant difference between BHA and the BHX/BHXB scan types. This increased thoracic expansion is the primary advantage to placing the reflector block on the xiphoid in order to decrease heart dose. Application of the neoprene-velcro belt (BHXB scans) to increase thoracic expansion resulted in a slightly larger mean MHD compared with the BHX scan type, however most volunteers displayed little improvement when the belt was applied and for one
volunteer it had a detrimental effect on MHD. In addition the mean left ventricle
doses for the BHX and BHXB scans were approximately the same. Based on
these findings I would exclude the use of a neoprene-velcro belt for abdominal
compression as no substantial benefit was observed. Based on the results of this
study, future research into the reproducibility of the MHD with the BHX scan
technique could help define the internal margins required for optimal target
coverage. Future studies for the BHX scanning technique could also include lung
cancer patients. The inferior heart shift during DIBH could result in significant
heart dose sparing for the treatment of tumors located in the superior portions of
the lungs and lung expansion could have the same effect for tumors located in
the lateral portions of the lungs.

Although great care was taken to contour all 215 structures used in this
study as accurately as possible, minor deviations in structure volume and
position must be taken into consideration. In addition, all female volunteers,
except 1(CS8), wore sports bras and had their left arms by their sides. This made
the PTV contour (left breast) and body contour surrounding the PTV very
subjective as typically the left breast would be positioned in a more lateral and
posterior position.
Figure 24: DVH for CS1 comparing dose to the Left Ventricle (LV) and Whole Heart (WH) for the Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB).
Figure 25: DVH for CS2 comparing dose to the Left Ventricle (LV) and Whole Heart (WH) for the Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB).
Figure 26: DVH for CS3 comparing dose to the Left Ventricle (LV) and Whole Heart (WH) for the Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB).
Figure 27: DVH for CS4 comparing dose to the Left Ventricle (LV) and Whole Heart (WH) for the Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB).
Figure 28: DVH for CS5 comparing dose to the Left Ventricle (LV) and Whole Heart (WH) for the Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB).
Figure 29: DVH for CS6 comparing dose to the Left Ventricle (LV) and Whole Heart (WH) for the Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB).
Figure 30: DVH for CS7 comparing dose to the Left Ventricle (LV) and Whole Heart (WH) for the Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB).
Figure 31: DVH for CS9 comparing dose to the Left Ventricle (LV) and Whole Heart (WH) for the Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB).
Figure 32: DVH for CS10 comparing dose to the Left Ventricle (LV) and Whole Heart (WH) for the Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB).
Figure 33: DVH for CS11 comparing dose to the Left Ventricle (LV) and Whole Heart (WH) for the Free Breathing (FB) and Deep Inspiration Breath-Hold techniques, Breath-Hold Abdomen (BHA), Breath-Hold Xiphoid (BHX), Breath-Hold Xiphoid with Belt (BHXB).
Appendix B

Examples of Maximum Heart Distance (MHD) Measurement

Figure 34: Maximum Heart Distance (MHD) measurements of CS1 for the various scan types: a) Free Breathing (FB), and Deep Inspiration Breath-Hold techniques, b) Breath-Hold Abdomen (BHA), c) Breath-Hold Xiphoid (BHX), d) Breath-Hold Xiphoid with Belt (BHXB).

Figure 35: Maximum Heart Distance (MHD) measurements of CS3 for the various scan types: a) Free Breathing (FB), and Deep Inspiration Breath-Hold techniques, b) Breath-Hold Abdomen (BHA), c) Breath-Hold Xiphoid (BHX), d) Breath-Hold Xiphoid with Belt (BHXB).
Figure 36: Maximum Heart Distance (MHD) measurements of CS8 for the various scan types: a) Free Breathing (FB), and Deep Inspiration Breath-Hold techniques, b) Breath-Hold Abdomen (BHA), c) Breath-Hold Xiphoid (BHX), d) Breath-Hold Xiphoid with Belt (BHXB).

Figure 37: Maximum Heart Distance (MHD) measurements of CS11 for the various scan types: a) Free Breathing (FB), and Deep Inspiration Breath-Hold techniques, b) Breath-Hold Abdomen (BHA), c) Breath-Hold Xiphoid (BHX), d) Breath-Hold Xiphoid with Belt (BHXB).
APPENDIX C

Examples of Inferior Heart Shift Measurements

Figure 38: Inferior heart shift measurements of CS1 for the various scan types: a) Free Breathing (FB), and Deep Inspiration Breath-Hold techniques, b) Breath-Hold Abdomen (BHA), c) Breath-Hold Xiphoid (BHX), d) Breath-Hold Xiphoid with Belt (BHXB).
Figure 39: Inferior heart shift measurements of CS3 for the various scan types: a) Free Breathing (FB), and Deep Inspiration Breath-Hold techniques, b) Breath-Hold Abdomen (BHA), c) Breath-Hold Xiphoid (BHX), d) Breath-Hold Xiphoid with Belt (BHXB).
Figure 40: Inferior heart shift measurements of CS4 for the various scan types: a) Free Breathing (FB), and Deep Inspiration Breath-Hold techniques, b) Breath-Hold Abdomen (BHA), c) Breath-Hold Xiphoid (BHX), d) Breath-Hold Xiphoid with Belt (BHXB).
Figure 41: Inferior heart shift measurements of CS8 for the various scan types: a) Free Breathing (FB), and Deep Inspiration Breath-Hold techniques, b) Breath-Hold Abdomen (BHA), c) Breath-Hold Xiphoid (BHX), d) Breath-Hold Xiphoid with Belt (BHXB).
BIBLIOGRAPHY


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