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Original Article

Exploring health effects of 6 and 15 MV X-ray photons in breast cancer therapy on heart and lung

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Abstract

***Background & Aims*:** In cancer patients, radiation therapy is vital but can lead to long-term side effects due to exposure of healthy tissues. This study focuses on breast cancer patients, where unintended radiation can affect organs like the heart and lung. This study investigates how photon radiation energy impacts dose distribution in tumors, heart, and lung post-radiation therapy.

***Materials & Methods*:** Data from computed tomography (CT) scans of 20 female breast cancer patient's post-mastectomy were analyzed. Treatment plans using 6 and 15 Mega-Volts (MV) energies for each patient were compared. The study considered a dose of 5000 cGy for each patient, evaluating conformity and homogeneity in the target volume, alongside average doses to sensitive organs using dose-volume histograms (DVH).

***Results*:** The results indicated that 15 MV energy reduced heart and lung doses compared to 6 MV during breast radiation therapy. Average heart doses at 6 and 15 MV were 706.15 and 630.35 cGy, respectively, and lung doses were 1630.05 and 1555.03 cGy, respectively. While 15 MV energy benefited organ doses, 6 MV provided better uniformity and homogeneity in dose distribution within the target volume.

***Conclusion*:** This study demonstrated significant differences in the dose received by organs at risk such as the heart and lung during radiation therapy with different photon energies, highlighting the importance of selecting the appropriate energy in safeguarding and health of vital organs.

***Keywords*:** Breast cancer, Health effects, Heart and lung, High energy photon, Organ doses, Radiation therapy

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Introduction

Breast cancer is the most common cancer and the fifth leading cause of death among Iranian women (1). Most breast cancer patients are treated surgically in the early stages. A meta-analysis conducted in 2005 showed that the risk of recurrence in the chest cavity of patients undergoing radiotherapy after mastectomy significantly decreases (2). Long-term follow-ups have indicated that unintended radiation exposure to heart structures can lead to an increased risk of death from heart diseases, particularly within 10 years after radiotherapy (3).

Treatments on breast cancer patients show that the left breast receives a higher unintended dose to the heart compared to the right breast (4). According to a report published in Canada, the risk of death from cardiotoxicity in left-sided radiation was 2% compared to 1% in right-sided radiation (5).

Currently, radiotherapy dosimetry data are somewhat available, but published data on the percentage of irradiated volumes with different doses are limited. Such information can be valuable for evaluating the relationship between heart and lung diseases due to unintended radiation exposure to these two sensitive body parts following radiotherapy, as the volumetric percentage of the heart or lung receiving a specific threshold dose can serve as a good predictor of the likelihood of death from heart and lung diseases.

There is also a risk of secondary lung malignancy (SLM) in women who have undergone breast radiation therapy after surgery. With the increased use of adjuvant breast radiation, the concerns about SLM have gained prominence and the prognosis has improved over the past decade. Furthermore, the latency period of radiation-induced secondary cancers is mostly over 10 years with the risk persisting for 30 to 40 years after treatment. Therefore, that is important to evaluate the absorbed dose of lung (6).

During treatment planning, parameters such as maximum dose, minimum dose, average dose, and dose received by the target volume are determined by examining DVH curves and isodose lines. Unfortunately, the large volume of data presented in these graphs, lines, and curves can complicate interpretation. Therefore, it is essential to use other parameters in addition to the available information to simplify the evaluation of treatment plan quality. The conformity index (CI) and homogeneity index (HI) are parameters that, using the information obtained from them, can help create better treatment plans that have a more homogeneous target volume and better protect normal tissues.

Another challenge in radiotherapy is selecting the appropriate energy to design a suitable radiotherapy regimen that results in a more uniform dose distribution in the target volume and minimal adverse effects on the patient (7). Despite the use of modern therapeutic systems, such as intensity modulated radiation therapy (IMRT), and the presentation of more homogeneous dose distributions in the planning target volume (PTV) by them, the evaluation of the treatment effects of these systems on sensitive organs such as the heart and lung remains crucial, and the resulting dose is not negligible (8, 9). At present, numerous linear accelerators generate photon energies of 6 and 15 MV, commonly employed in breast cancer radiotherapy. However, determining the optimal energy for breast cancer radiotherapy is a subject of ongoing discussion (10). Most breast cancer 3D conformal radiotherapy treatments use 6 MV photons, but in some cases, such as treating large breasts with distances greater than 24 centimeters, for example, higher energy X-rays are used to eliminate hot spots (11).

The aim of this study was to compare the effects of high-energy photons (6 and 15 MV) on the doses received by the heart and lung in 20 left breast cancer patients who had undergone mastectomy. In this study, in addition to DVH curves, CI and HI in the target volume were extracted and examined to identify the optimal photon energy of treatment plan.

Materials & Methods

This study was conducted using CT images of 20 female breast cancer patients who had undergone mastectomy and received radiotherapy. Two photon energies of 6 and 15 MV were used. All patients were scanned using a spiral CT system (Siemens Company Product, Germany) under identical treatment conditions. Subsequently, the CT images were imported into the CorePLAN Treatment Planning System (TPS) which had been commissioned with data from the Siemens Primus linear accelerator. After importing the CT images into the 3D treatment planning system, all slices of the target region, including the clinical target volume (CTV), PTV, as well as the heart and lung as organs at risks, were contoured. The breast target volume should receive 95% of the prescribed dose or be encompassed by the 95% isodose line. All treatment plans were approved by an oncologist and implemented using the CorePLAN TPS for 6 and 15 MV energies. This treatment design system uses the collapsed cone convolution and equivalent tissue air ratio (ETAR) algorithm for dose calculations. The treatment design for breast cancer radiotherapy with a dose of 5000 cGy in 25 sessions was performed conformally. Two tangential fields and one supraclavicular field were used. Cerrobend blocks were used to achieve appropriate dose coverage in the target area and protect organs at risk. In order to study the effect of photon energy on the dose distribution in PTV and organs at risk including the heart and lung, other treatment plan parameters such as the number of fields, prescribed dose, and the method of maintaining consistent protection were also considered. To evaluate the quality of the treatment plans for the studied patients, DVH curves for PTV and the heart and lung as vital organs were calculated and compared for 6 and 15 MV photon energies. Additionally, in order to select the optimal photon energy in terms of more homogeneous dose distribution in the PTV region, CI and HI were evaluated using TPS data. HI is defined as:

$$HI = {}^{D_{5\%}}/_{D_{95\%}}$$

where D5% is the dose received by 5% of the tissue volume and D95% is the dose received by 95% of the tissue volume (9). By selecting the 95% isodose line, CI is defined as (7):

$$CI = \frac{Volume \text{ within 95\% isodose line}}{Volume \text{ of PTV}}$$

The closer these two parameters are to 1.0, the better the homogeneity and alignment we have. For statistical analysis of the study results, a paired sample t-test was performed using SPSS software version 13, with a significance level of $p < 0.05$.

Results

Mean and Maximum Dose of Heart and Lung

After conducting treatment planning for each of the 20 patients under the supervising of an oncology specialist, the average and maximum doses were extracted using DVH for each organ at risk (OAR) and for both 6 and 15 MV photon energies. The mean dose to the heart for 6 and 15 MV photons was determined to be 706 cGy and 630 cGy, respectively. Statistical paired-sample t-test analysis indicates a significant difference between the mean dose of heart for 6 and 15 MV ($p < 0.05$). Table 1 displays the mean and maximum doses corresponding to the two photon energies. Statistical analysis shows no significance difference between maximum dose of heart for both energies. Figures 1 and 2 illustrate a visual comparison between the mean and maximum absorbed doses for the two photon energies.

Table 1. Mean and maximum heart doses for 6 and 15 MV photon beams

Photon energy	Mean dose ± SD (cGy)	Maximum dose ±SD (cGy)
6 MV	706 ± 265	5041 ± 668
15 MV	630 ± 253	4874 ± 351

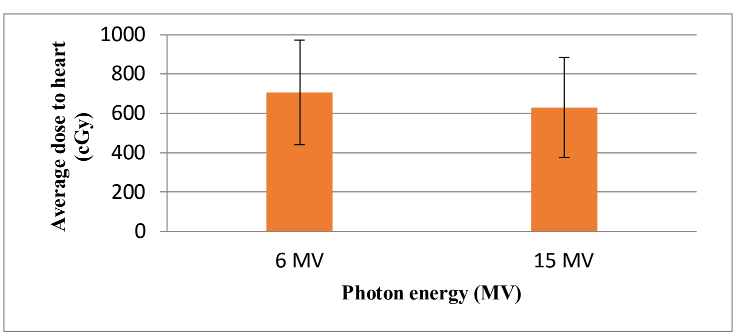

Fig. 1. Comparison of mean heart doses for 20 patients using 6 and 15 MV photon energies

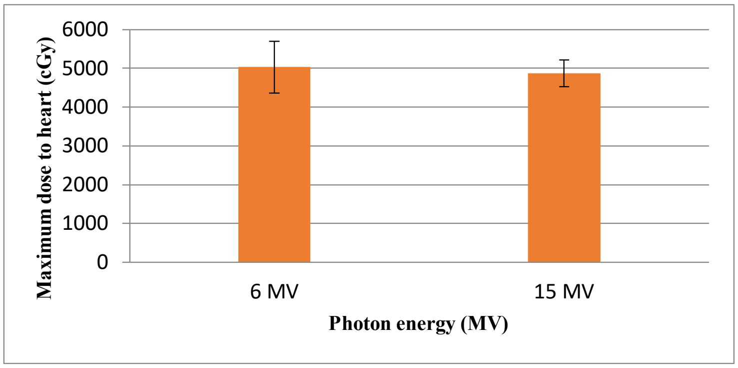

Fig. 2. Comparison of maximum heart doses for 20 patients using 6 and 15 MV photon energies

In this study, another organ at risk (OAR) considered was the lung. The data from the TPS for the 20 patients indicated that the mean lung doses resulting from planning with 6 and 15 MV photons were 1630 cGy and 1555 cGy, respectively. Statistical paired-sample t-test analysis indicates a significant difference between the mean and maximum dose of lung for 6 and 15 MV ($p < 0.05$). Table 2, Figure 3, and Figure 4 present the TPS results for lung doses.

Table 2. Mean and maximum lung doses for 6 and 15 MV photon beams

Photon energy	Mean dose ± SD (cGy)	Maximum dose ± SD (cGy)
6 MV	1630 ± 137	5595 ± 215
15 MV	1555 ± 143	5420 ± 230

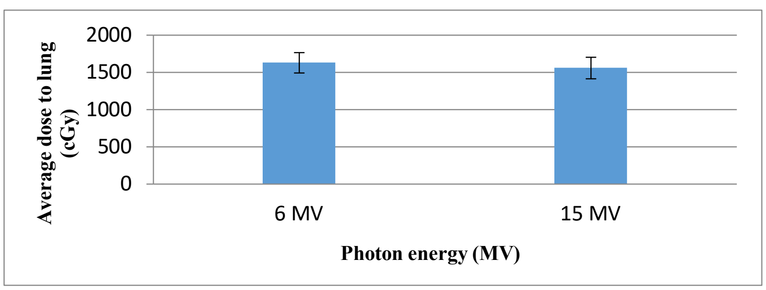

Fig. 3. Comparison of mean lung doses for 20 patients using 6 and 15 MV photon energies

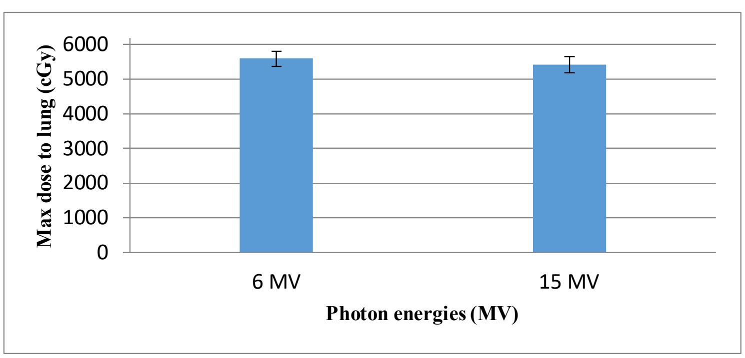

Fig. 4. Comparison of maximum lung doses for 20 patients using 6 and 15 MV photon energies

Uniformity and Homogeneity of Dose

The final data to assess the quality of dose distribution in the PTV should be extracted from the DVHs. The parameters used to evaluate the fitness of the dose distribution quality are the CI and HI. Table 3 presents the results of the HI for treatment planning using 6 and 15 MV photons.

Statistical paired-sample t-test analysis indicates a significant difference between the HI of the 6 and 15 MV photon treatment groups ($p < 0.05$). Additionally, a one-sample t-test analysis reveals a significant difference between the HI and 1 ($p < 0.05$).

Table 3. Mean homogeneity index of treatment doses for patients treated with 6 and 15 MV photons

Photon energy	Mean HI ± SD
6 MV	1.16 ± 0.05
15 MV	1.26 ± 0.08

Additionally, Table 4 displays the results for the Mean CI of two types of plans using 6 and 15 MV photon beams for all patient treatment plans.

Table 4. Mean conformity index of treatment doses for patients treated with 6 and 15 MV photons

Photon energy	Mean CI ± SD
6MV	0.91 ± 0.10
15MV	0.73 ± 0.17

Statistical paired-sample t-test analysis indicates a significant difference between the conformity indexes (CI) of the 6 and 15 MV photon treatment groups ($p < 0.05$). Additionally, a one-sample t-test analysis reveals a significant difference between the CI and 1 for both groups ($p < 0.05$).

Discussion

In the present study, the effect of 6 and 15 MV radiation energies on dose distribution in the target volume and organs at risk (lung and heart) were investigated. X-rays generated from the Siemens Primus accelerator at two energies, 6 and 15 MV, were used, with 6 MV typically applied in breast radiotherapy. Considering the development of new devices and the possibility of accessing higher energies, these energies need to be examined to determine the advantages and disadvantages of each photon energy so that the appropriate energy can be selected under different conditions. Therefore, in this study, the dose distribution resulting from 6 and 15 MV energies for 20 female patients was studied, and for each patient, the average and maximum dose received by the heart and lung, as well as the HI and CI at the two high and low energies (6 and 15 MV) were investigated and compared.

Based on the calculations, the mean of HI for 6 and 15 MV are 1.16 and 1.26, respectively (Table 3). In the t-test, the difference in HI between the two photon energies under investigation is significant ($p < 0.05$). These values, according to the One Sample T-test at 6 and 15 MV with a significant difference, indicate a deviation from the ideal value of one, showing that the dose homogeneity in the target volume is not ideal. However, based on comparing the means, HI is closer to 1.0 at 6 MV.

The mean values of the CI for 6 and 15 MV are calculated to be 0.91 and 0.73, respectively (Table 4), showing a significant difference ($p < 0.05$). According to the One Sample T-test, the difference in CIs from the value of one is significant, indicating a deviation from the ideal value of one in the target volume. Again, based on comparing the means, CI is closer to one at 6 MV, and the volume that receives 95% of the dose is higher at 6 MV.

The mean and maximum doses received by the heart in patients treated with 15 MV photons are lower than those treated with 6 MV (Table 1). The use of 15 MV photons results in a decrease in the average heart dose by 76 cGy and a decrease in the maximum heart dose by 167cGy. The difference in average doses is significant, but the difference in maximum heart doses is not ($p < 0.05$).

Similarly, the average and maximum doses received by the lung in patients treated with 15 MV photons are lower than those treated with 6 MV (Table 2). The results show that the use of 15 MV photons leads to a reduction in the average lung dose by 75 cGy and a decrease in the maximum lung dose by 175cGy. All differences related to average and maximum lung doses are statistically significant ($p < 0.05$).

Therefore, may be due to large angle of scattering of higher energy photons, the average and maximum doses received by the heart in treatment with 15 MV energy are lower compared to treatment with 6 MV energy. Additionally, the reduction in lung dose at higher energy (15 MV) may be due to the lower lung density. The increase in the number of electrons that go outside the treatment field due to the lower lung density leads to a decrease in the absorbed dose. Consequently, scattered electrons decrease more laterally, resulting in a reduced dose at the central axis of the beam. This effect is more pronounced for higher than 6 MV photon energies (10).

However, this study shows that, at 15 MV, the CI and HI of the treatment region deviate more from the value of 1.0, indicating better conformity and homogeneity and hence better coverage of the target volume in treatment with 6 MV energy.

According to a study by Darby et al., who investigated the risk of ischemic heart disease in patients undergoing surgery and radiotherapy for breast cancer, the relative risk increases by 7.4% for every one gray increase in the dose received by the heart (11). Based on this finding, the difference in heart dose between treatment with two photon energies, 6 and 15 MV, is significant in terms of causing cardiac issues.

In a systematic review conducted by Taylor et al., the radiation doses received by the heart during radiotherapy for left breast cancer between 2003 and 2013 were analyzed. For 91% of the patients included in the study, the prescribed dose fell within the range of 40 to 50.7 gray. The average heart dose for all 398 treatment regimens documented across 149 articles from 28 different countries was found to be 11% of the prescribed dose. Among the various countries studied, the average heart doses in Saudi Arabia, China, and Germany were calculated to be 16%, 12%, and 13%, respectively, which closely align with the values obtained in our current study (14% for 6 MV and 13% for 15 MV). Furthermore, as per the study findings, patients who also received radiation to the supraclavicular region separately were exposed to a cardiac dose ranging from 14% to 16% of the prescribed dose (3).

In 2012, Ng et al. investigated the risk of secondary lung disorders in patients who underwent surgery and received radiotherapy for breast cancer (50 gray in 25 sessions). In that study, the average received lung dose was calculated to be 13%, but in the current study, the average lung dose was found to be 32% for 6 MV and 31% for 15 MV. The reason for this difference may be due to the lack of differentiation between patients with left breast cancer and those with right breast cancer in the mentioned study (6). However, in a research conducted in 2012 by Assaoui et al., patients with left breast cancer who underwent radiotherapy with 6 MV photons after surgery were examined (13). In the current study, the average lung dose was evaluated to be 32%, which is consistent with the value obtained for 6 MV photons in the Assaoui et al. study. Furthermore, according to Assaoui et al., V20 was calculated to be 33%, which is 28.01% for 6 MV and 27.5% for 15 MV in our study. In 2023, Omidvar S. et al. in a study showed that the risk of cardiac mortality and pneumonitis in conventional radiotherapy regimen is significantly high, so choosing a proper photon energy is essential for healthy treatment of breast cancer patients (14).

Additionally, a review study of Damein et al. in 2006, showed that the average lung dose in three different studies were 33.3%, 29%, and 22.5%, which are consistent with the values obtained in our study (15). The CI value in the mentioned three different independent studies were calculated as 0.86, 0.89, and 0.92, and in our study, this variable is 0.91 for 6 MV and 0.73 for 15 MV.

Conclusion

In this study, a comparison was made between breast cancer treatment using 6 and 15 MV photon energies. Selecting the appropriate energy for treatment can vary depending on different health conditions and various patient organs such as the heart and lung. Typically, to achieve better PTV coverage, treatment is carried out using 6 MV photon energy. However, if a patient has heart or lung issues where unintended dose escalation to these organs could lead to dysfunction, or in cases where the patient has previously received doses to the heart or lung and requires re-irradiation in areas near these organs, and the treatment planner aims to reduce the dose received by these organs, 15 MV energy may be considered as one of the selectable options. It should be noted, though, that the homogeneity and conformity indices at this energy level may differ from those at 6 MV, potentially resulting in reduced homogeneity and conformity within the target volume.

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Author’s Contributions

Hassan Saberi and Ahad Zeinali supervised, conceptualized, and wrote the initial draft. Mahshad Neshasteriz (M.Sc. Student) investigated and analyzed the data. Mohsen Hoseini and Laya Karimkhani checked validation and resources.

Data Availability

The raw data of the article are available from the authors upon reasonable request.

Conflict of Interest

The authors have no conflict of interest associated with the material presented in this paper.

Ethical Statement

The article is extracted from the M.Sc. thesis of Ms. Mahshad Neshasteriz with the code of ethics IR.UMSU.REC.1393.269.

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