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Image guidance during breast radiotherapy: A phantom dosimetry and radiation-induced second cancer risk study

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Abstract

Imaging procedures utilised for patient position verification during breast radiotherapy can add a considerable dose to organs surrounding the target volume on top of therapeutic scatter dose. This study investigated the dose from a breast kilovoltage cone-beam CT (kV-CBCT), a breast megavoltage fan-beam CT (MV-FBCT), and a TomoDirectTM breast treatment. Thermoluminescent dosimeters placed within a female anthropomorphic phantom were utilised to measure the dose to various organs and tissues. The contralateral breast, lungs and heart received 0.40 cGy, 0.45 cGy and 0.40 cGy from the kV-CBCT and 1.74 cGy, 1.39 cGy and 1.73 cGy from the MV-FBCT. In comparison to treatment alone, daily imaging would increase the contralateral breast, contralateral lung and heart dose by a relative 12%, 24% and 13% for the kV-CBCT, and 52%, 101% and 58% for the MV-FBCT. The impact of the imaging dose relative to the treatment dose was assessed with linear and linear-quadratic radiation-induced secondary cancer risk models for the contralateral breast. The additional imaging dose and risk estimates presented in this study should be taken into account when considering an image modality and frequency for patient position verification protocols in breast radiotherapy.

Keywords

risk, study, second, induced, radiation, cancer, dosimetry, image, phantom, radiotherapy, breast, during, guidance

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Abstract. Imaging procedures utilised for patient position verification during breast radiotherapy can add a considerable dose to organs surrounding the target volume on top of therapeutic scatter dose. This study investigated the dose from a breast kilovoltage cone-beam CT (kV-CBCT), a breast megavoltage fan-beam CT (MV-FBCT), and a TomoDirect™ breast treatment. Thermoluminescent dosimeters placed within a female anthropomorphic phantom were utilised to measure the dose to various organs and tissues. The contralateral breast, lungs and heart received 0.40 cGy, 0.45 cGy and 0.40 cGy from the kV-CBCT and 1.74 cGy, 1.39 cGy and 1.73 cGy from the MV-FBCT. In comparison to treatment alone, daily imaging would increase the contralateral breast, contralateral lung and heart dose by a relative 12%, 24% and 13% for the kV-CBCT, and 52%, 101% and 58% for the MV-FBCT. The impact of the imaging dose relative to the treatment dose was assessed with linear and linear-quadratic radiation-induced secondary cancer risk models for the contralateral breast. The additional imaging dose and risk estimates presented in this study should be taken into account when considering an image modality and frequency for patient position verification protocols in breast radiotherapy.

1. Introduction

Three-dimensional image guidance during breast radiotherapy is becoming more common and has been found to be more effective in comparison to two-dimensional image verification based on bony anatomy information [1]. However, these additional images will increase the dose to organs and tissues adjacent the treated breast, which would not receive a large dose from treatment alone. This may increase the likelihood of long-term side effects such as secondary cancers occurring [2]. An increased long-term risk of secondary cancer in the contralateral breast has been observed for breast radiotherapy patients who receive a dose of 1 Gy or more to the contralateral breast [2].

This study investigated the dose to various organs and tissues from a single kV-CBCT and a single MV-FBCT acquired for breast patient position verification as well as a TomoDirect™ breast tomotherapy treatment. The risk of developing a radiation-induced secondary contralateral breast cancer was estimated with a general linear quadratic model [3], a linear quadratic model incorporating fractionation [4], and a excess relative risk model [5].

2. Materials and methods

2.1. Dosimetry, phantom, treatment and imaging

The dose from a kilovoltage cone-beam CT (kV-CBCT), megavoltage fan-beam CT (MV-FBCT), and a 2-field TomoDirect™ breast treatment were evaluated for a female anthropomorphic phantom (CIRS Inc., Norfolk VA, USA).

kV-CBCT imaging was performed on an Elekta Synergy XVI system (Elekta; Stockholm, Sweden) with the phantom setup on a breast board. The image protocol involved a 270° arc rotation (clockwise 270° to 180°), with 120 kVp, 20 mA and 20 ms per frame, field-of-view size S20, no filter (F0), and with approximately 350 frames collected per scan.

The breast treatment and MV-FBCT scan were performed on a Tomotherapy unit (Tomotherapy Inc., Madison WI, USA). The MV-FBCT was acquired with 3.5 MV photons, pitch of 8.0 (normal), jaw width 1 mm, and field length 15.6 cm. The TomoDirect™ treatment consisted of 2.5 cm jaw width, modulation factor 3.0, pitch 0.287, and beam angles 117° and 308°.

Lithium-fluoride thermoluminescent dosimeters (TLD-100H; Harshaw, Germany), size 3.2 x 3.2 x 0.4 mm^3 were placed throughout the phantom at locations representing organs and tissues. A Harshaw 5500 reader was utilised with a read-out cycle which included a preheat of 100°C for 10 seconds (s) and a linear ramp of 20°Cs^{-1} to 235°C for 20 s. The chips were annealed at 240 ± 2°C for 15 minutes and cooled rapidly on a steel block. For the kV-CBCT measurements the TLDs were calibrated with an orthovoltage machine (Pantak Therapax 300; Elimpex-Medizintechnik, Austria), with beam energy 135 kVp. TLDs were calibrated on a Varian Clinac linear accelerator (Varian Medical Systems Inc., Palo Alto CA, USA) for the MV-FBCT and TomoDirect™ measurements. Individual chip calibration factors were determined and only TLD chips with a reproducibility of ± 3% were used. Dose measurements were repeated twice with two TLD chips at each measurement location.

2.2. Contralateral breast secondary cancer risk

The risk of developing a radiation-induced cancer in the contralateral breast was estimated for treatment with nil imaging and treatment plus daily imaging (25 scans) for both image modalities. Three risk models were utilised; the UNSCEAR general linear quadratic model [3], the Dasu *et al* linear quadratic model incorporating the influence of fractionation [4], and the Preston *et al* excess relative risk (ERR) model [5]. The UNSCEAR [3] general linear quadratic model:

$$Effect = (\alpha_1 D + \beta_1 D^2) \times e^{-(\alpha_2 D + \beta_2 D^2)} \qquad (1)$$

where D is the mean contralateral breast dose (Gy) from total treatment. The first term of the equation accounts for radiation-induced DNA mutations, α_1 and β_1 values of 0.02 Gy^{-1} and 0.005 Gy^{-2} were utilised in this study, and the second term represents cell survival, α_2 and β_2 values of 0.25 Gy^{-1} and 0.06 Gy^{-2} were utilised in this study.

The Dasu *et al* [4] linear quadratic model with a fractionation parameter:

$$Effect = \left(\alpha_1 D + \frac{\beta_2 D^2}{n}\right) \times e^{-\left(\alpha_2 D + \frac{\beta_2 D^2}{n}\right)} \qquad (2)$$

where n in the number of fractions (25 for this study). To enable comparison with the ERR model below, the risk values calculated above were multiplied with a factor B [6] which depends upon demographic and cohort factors, such that $ERR = B \times Effect$.

The Preston *et al* ERR model [5] was developed from work which examined the breast incidence associated with imaging and low therapeutic doses:

$$ERR = D \times \beta \times \left(\frac{age}{50}\right)^{\gamma} \qquad (3)$$

where β is the ERR/Gy and γ is an exponent of attained age. The ERR model parameters were obtained from cohorts receiving similar dose values to those investigated in this study, this included

the New York acute post-partum mastitis cohort and the Massachusetts tuberculosis fluoroscopy cohort and its extension cohort. From this, parameters β and γ were determined to 0.68 and -1 respectively [5].

3. Results

The dose to organs from a single breast TomoDirect™ fraction, single kV-CBCT, and a single MV-FBCT acquired for patient position verification in breast radiotherapy are displayed in table 1. The cumulative dose and secondary cancer risks to the contralateral breast from treatment with nil imaging, treatment plus daily kV-CBCT and treatment plus daily MV-FBCT are outlined in table 2.

Table 1: Organ doses from a single breast TomoDirect™ fraction, a single breast kV-CBCT, and a single breast MV-FBCT.

Organ	Dose (cGy)		
	TomoDirect™	kV-CBCT	MV-FBCT
Ipsilateral breast	199.91 ± 8.32	0.51 ± 0.03	1.74 ± 0.11
Contralateral breast	3.32 ± 0.29	0.40 ± 0.01	1.74 ± 0.11
Ipsilateral lung	23.59 ± 2.92	0.45 ± 0.02	1.34 ± 0.15
Contralateral lung	1.38 ± 0.07	0.33 ± 0.01	1.39 ± 0.14
Heart	2.98 ± 0.14	0.40 ± 0.01	1.73 ± 0.08

Table 2: The cumulative dose and excess relative risk to the contralateral breast from treatment with nil imaging, treatment plus daily kV-CBCT imaging and treatment plus daily MV-FBCT imaging.

	Treatment with nil imaging	Treatment plus daily kV-CBCT	Treatment plus daily MV-FBCT
Dose (Gy)	0.83 ± 0.07	0.99 ± 0.11	1.27 ± 0.08
Excess relative risk			
UNSCEAR [3]	0.53	0.62	0.75
Dasu *et al* [4]	0.46	0.53	0.63
Preston *et al* [5][a]	0.47	0.56	0.72

[a]estimated for attained age 60-years, for women treated at age 50-years. A 10-year latency period for radiation-induced secondary malignancy is within the time period, 5-14 –years where Clarke et al [7] found an excess of contralateral breast cancers after breast radiotherapy.

4. Discussion

For the breast patient position verification image protocols investigated in this study, the kV-CBCT was found to deliver a lower dose in comparison to the MV-FBCT. If utilised for daily image guidance the patient dose would be increased by up to a maximum 12.8 cGy for the kV-CBCT and up to 43.5 cGy for the MV-FBCT. Patient position verification does not increase the dose to the target volume greatly, daily imaging increases the dose to the treated breast by a relative 0.3% and 0.9% for the kV-CBCT and MV-FBCT respectively. However for organs surrounding the treated breast, treatment with daily imaging in comparison to treatment with nil imaging, increases in the contralateral breast, contralateral lung and heart dose by a relative 12%, 24% and 13% for the kV-CBCT and 52%, 101% and 58% for the MV-FBCT. For this reason, imaging dose needs to be quantified in order to assess potential long-term risks, such as secondary cancer.

The significance of the imaging dose relative to the treatment dose was assessed for the contralateral breast with three secondary cancer risk models. The ERR estimates were similar for all three models, agreeing to within 9%. This is attributed to the low dose received by the contralateral breast for the treatment and imaging protocols. For low doses the second term in the linear quadratic

models [3, 4] becomes negligible and thus the risk estimates linear. The dose-risk relationship for low doses (less than 1 Gy) is controversial [8] however a linear-no-threshold model is generally recommended for low doses [3, 9, 10]. MV-FBCT daily imaging was determined to increase the ERR by up to a relative 53% in comparison to treatment with nil imaging.

5. Conclusion

The MV-FBCT delivered a greater dose in comparison to the kV-CBCT for breast radiotherapy image guidance. Daily imaging was found to deliver a dose of 10.0 cGy and 12.8 cGy to the contralateral breast and ipsilateral breast for the kV-CBCT, and 43.5cGy and 43.5 cGy for the MV-FBCT. In comparison to treatment alone, the treatment plus daily imaging would increase the contralateral breast and ipsilateral breast dose by a relative 12% and 0.3% for the kV-CBCT, and 52% and 0.9% for the MV-FBCT. Thus, daily imaging increased the estimated risk of developing a radiation induced contralateral breast cancer relatively by up to 53% (MV-FBCT with the Preston *et al* ERR model). The dose and risk estimates presented in this study may help clinicians make informed decisions on the image modality type and image frequency required for patient position verification in breast radiotherapy.

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