Determination of the appropriate physical density of internal metallic ports in temporary tissue expanders for the treatment planning of post-mastectomy radiation therapy

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ABSTRACT

Some patients undergoing breast reconstruction require post-mastectomy radiation therapy, but the metallic ports used in temporary tissue expanders attenuate the X-rays. In this study, we evaluated by the film method, the attenuation of 4 MV and 6 MV X-rays after passing through a metallic port, with the aim of identifying a useful method for determining the appropriate density to use in the radiation treatment planning system (RTPS), taking into account the distance between the metallic port and the targets. Radiochromic film was used to measure depth doses after the X-rays passed through the metallic port. The physical density allotted to the metal port portion was varied on the RTPS within the range 1–16 g/cm³, and the physical density values were calculated that best reproduced the depth-dose distribution extrapolated from the film method. When the metallic port was orientated perpendicularly, the attenuation of the X-rays peaked at ~7% at both 4 MV and 6 MV. In the parallel orientation, the X-rays were attenuated by up to ~40% at 4 MV and by up to ~30% at 6 MV. We estimated the optimum physical density to be 9.8 g/cm³, which yielded the best fit with the actual measurements. We demonstrated the most likely range for the target depth from the CT images of actual patients and, within this range, we identified the optimum physical density at which the measured and calculated values were most consistent with each other.

Keywords: breast cancer; post-mastectomy radiation therapy; tissue expander; high-density inhomogeneity

INTRODUCTION

Post-mastectomy radiation therapy (PMRT) is an important therapeutic modality for high-risk breast cancer patients because it can reduce the recurrence of localized carcinomas, thereby improving life expectancy [1]. Breast reconstruction is beneficial for improving the quality of life for a patient who has undergone a mastectomy, by alleviating the associated aesthetic deterioration [2, 3]. Implant reconstruction is a frequently employed modality for breast...
reconstruction because of its less invasive nature. In many cases, this can involve placing a temporary tissue expander (TTE) on the chest wall during mastectomy, which is then expanded over the following months by injecting physiological saline, causing the skin on the patient’s chest to stretch. After the skin has stretched sufficiently, a permanent implant made of a material such as silicone is surgically inserted. In most cases, the TTE is fitted with a metallic port through which physiological saline is injected. This is usually equipped with a magnetic disk made from rare earth elements of high atomic number, which is used to guide the injected saline into the implant valve. However, some patients who have undergone breast reconstruction need PMRT, and several studies have reported that the TTE magnet disks substantially attenuate X-rays passing through them [4–9]. In our institutions, PMRT with TTEs has been administered to patients with adverse pathological findings following preoperative chemotherapy in patients strongly desiring breast reconstruction.

In most current radiotherapy regimens, radiation treatment planning systems (RTPSs) are utilized to calculate and evaluate the radiation dose distribution. Generally, RTPS dose calculations convert CT values into either the physical density or the electron density relative to water. However, the metallic port, composed of high atomic number elements, yields CT values with a considerable level of uncertainty. Accurate reproduction of the dose attenuation by the metallic port therefore requires the appropriate densities to be allocated manually to the parts of CT images corresponding to the port. In a previous study, Chen et al. hypothesized a relative electron density of 11.8, with no mention of a specific physical density [9]. Determination of the appropriate density requires actual measurements for comparison with the calculated values. However, after X-rays pass through the metallic port, they undergo changes in their energy spectrum due to beam-hardening effects, thereby altering the slope of the attenuation curve. Because most currently available commercial RTPSs are incapable of accurately calculating such changes in energy, determining the density values consistent with actual measurements at every depth is not feasible. The area surrounding the metallic port is filled with physiological saline and contains no targets. Accordingly, the shallow areas immediately below the metallic port are likely to be of less clinical importance than the deeper areas, in which the targets are likely to be. However, few studies have investigated these problems. Furthermore, the studies cited earlier were predicated on an energy output of 6 MV or above, but many Japanese institutions generally use a nominal energy output of 4 MV X-rays for PMRT [4–9]. At 4 MV, X-rays would be expected to be more susceptible to attenuation when passing through the metal. The aim of the present study was therefore to evaluate, by the film method, the attenuation of 4 MV and 6 MV X-rays after they pass through a metal port, to help establish a useful method for determining the appropriate density to be used in the RTPSs, taking account of the distance between the metallic port and the target.

### MATERIALS AND METHODS

**Depth–dose measurement after passing through a metallic port**

Clinac 21EX (Varian Medical Systems, Inc., Palo Alto, CA, USA) was used as a radiation source of X-rays, output at either 4 MV or 6 MV. A film was placed inside a solid phantom (Tough Water WE211 Phantom, Kyoto Kagaku Co., Kyoto, Japan) parallel to the beam axis to measure the depth doses. With the same geometry, a metallic port (Magna-Site®, Inamed/Allergan, Santa Barbara, CA, USA; nominal physical density: 8.4 g/cm³) of an archetypal TTE (McGhan Style 133, Inamed/Allergan, Santa Barbara, CA, USA) was installed on the beam axis on the surface of the phantom. The gantry was angled at 0°, the source-to-surface distance was 100 cm, the radiation field size was 10 cm × 10 cm at its isocenter, and the output was 200 monitor units. Radiochromic film (Gafchrmic
EBT3 dosimetry film, ISP, Inc., Wayne, NJ, USA) was used; this has an extremely small energy dependence and so was considered a suitable choice as a detector for this study [10]. For the measurements, the metallic port was placed either perpendicularly (down-perpendicular orientation) or parallel (up-parallel orientation) to the beam axis (Fig. 1). The relative differences with and without the metallic port were calculated at the peak depth and at depths of 5, 10 and 15 cm. To illustrate changes in the slope of the attenuation curves, the percentage of the depth dose at 10 cm depth (PDD10) was calculated [11].

Calculation of the depth of each target
This study included data from 20 patients undergoing PMRT regimens at our institution, between 2007 and 2014. Taking the chest wall of each patient as the target, the longer and shorter distances between the metallic port and the chest wall were measured from the CT images (Fig. 2). The longer distance was defined by the path taken by the beam passing through the boundary of the metallic port to the skin, and the shorter one was defined as the distance from the boundary of the metallic port to the boundary of the TTE.

Determination of the optimum physical density
CT images were taken using the same geometry as that used during measurements. The physical density allotted to the metallic port portion was varied in the RTPS within the range 1.0 – 16.0 g/cm³ (specifically at 1.0 g/cm³, 8.0 – 11.0 g/cm³ in increments of 0.2 g/cm³, and 12.0 and 16.0 g/cm³) and the physical density values that would reproduce the depth-dose distribution extrapolated from the film method were calculated. The physical density values most consistent with the actual measurements were calculated at the target depths measured in the previous section. Thus, the physical density that would give the smallest sum of squared errors between the actual and calculated values at each density was defined as the optimal value. The Lightspeed RT16 CT scanner (GE Healthcare, Waukesha, WI, USA) was used to capture images at a slice thickness of 2.5 mm, reflecting clinical practice. The RTPS Pinnacle3 (version 9.0, Philips Radiation Oncology Systems, Fitchburg, WI, USA) was employed in combination with a collapsed cone convolution algorithm for dose calculation. The grid size for the dose calculations was set at 2 mm.

Dose calculations in the PMRT planning
Clinical PMRT plans for 20 patients were retrospectively re-planned in the Pinnacle3 RTPS using 4 MV and 6 MV photons to 50 Gy at 2 Gy per fraction. The plans were generated with the tangential field-in-field technique and used the same isocenter, gantry angle, and main-field apertures as those in the clinical plans for each patient. At our institution, PMRT is applied without a tissue-equivalent bolus for patients with a TTE inserted; however, in this study, all PMRT plans were re-planned with a 5-mm thickness bolus in consideration of the accuracy of the superficial dose calculations. For the purpose of this study, the clinical target volume for the evaluation (CTVeval) was defined as the volume from the chest wall excluding the volume of the TTE (Fig. 3). CT artifacts due to the metallic port within the patient were assigned the physical density 1.0 g/cm³, and those in the air were assigned 0 g/cm³. Two PMRT plans were generated for each patient and energy value. CTVeval values were evaluated by varying the physical density at

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Fig. 2. Example of the two measured distances between the metallic port and the chest wall. The longer distance is defined by the path taken by the beam passing through the boundary of the metallic port to the skin, and the shorter one is defined as the distance from the boundary of the metallic port to the boundary of the temporary tissue expander.

Fig. 3. Example of the clinical target volume for evaluation (CTVeval, marked in blue). The CTVeval included the area to the pleura or the ribs under the TTE.
which the metallic port was assigned 1.0 g/cm³ (PD1 plans) and using the optimum density determined as described in the previous section (OD plans). The energy dependence of the dose–volume data were compared for statistical significance using a paired t-test (using R version 3.4.1), with P < 0.05 considered significant.

RESULTS

Depth doses after passing through the metallic port

Figure 4 shows the changes in the depth–dose distribution with and without the metallic port, with 200 cGy of radiation defined as 100% for all cases. Table 1 compares the relative dose differences with and without the metallic port, as well as the changes in PDD₁₀ with or without the port. When the metallic port was placed in the down-perpendicular orientation, the attenuation of X-rays peaked at ~7% for both 4 MV and 6 MV. In the up-parallel orientation, the X-rays were attenuated by up to ~40% at 4 MV and up to ~30% at 6 MV. The greatest difference was observed in the shallow areas in the vicinity of the peak depth. The PDD₁₀ values at 4 MV and 6 MV were 61.6 and 66.8, respectively, without the metallic port; 63.1 and 67.7 with the port in the down-perpendicular orientation; and 70.8 and 71.3 in the up-parallel orientation.

Calculation of target depths

In the 20 subjects, the mean ± standard deviation [range] of the longer and the shorter distances were 5.7 ± 0.9 cm [4.3–7.2] and 2.4 ± 0.4 cm [2.0–3.5], respectively. This suggested that the target was highly likely to lie within 2–10 cm from the metallic port. Because of this, physical density values consistent with the actual measurements were calculated within the range 2–10 cm.

Optimum physical density

Figure 5 shows a comparison between the actual and calculated values of the percentage depth doses when the physical density allotted to the metal port portion was altered within the range 1.0–16.0 g/cm³. Within the range 2–10 cm, the optimum density of the metallic port that would yield the calculated value most consistent with the actual measurement was 9.8 g/cm³.

Dose attenuation volume in the PMRT planning

The OD plans were compared with the PD1 plans. Underdose regions on both sides of the metallic port were observed in all of the OD plans (Fig. 6). Table 2 presents the dose–volume data for CTVeval (mean, 109.7 cm³; range, 56.7–174.9 cm³), comparing the

Table 1. PDD₁₀ and differences in the dose at the peak depth and at depths of 5, 10 and 15 cm without the metallic port and with the port in the two orientations

| Parameter             | 4 MV without | 4 MV down | 4 MV up | 6 MV without | 6 MV down | 6 MV up |
|-----------------------|--------------|-----------|---------|--------------|-----------|---------|
| Depth of dose maximum | –            | –5.0%     | –38.8%  | –            | –4.4%     | –30.2%  |
| Depth, 5 cm           | –            | –6.9%     | –34.6%  | –            | –3.8%     | –26.9%  |
| Depth, 10 cm          | –            | –2.7%     | –29.7%  | –            | –3.1%     | –25.6%  |
| Depth, 15 cm          | –            | –1.4%     | –30.3%  | –            | –3.4%     | –25.1%  |
| PDD₁₀                 | 61.6         | 63.1      | 70.8    | 66.8         | 67.7      | 71.3    |

PDD₁₀ = percentage of the depth dose at 10 cm, without = without the metallic port, down = with the port in the down-perpendicular orientation, up = with the port in the up-parallel orientation.
OD plans with the PD1 plans. The V_{50 Gy} values (50 Gy was 100% of the prescribed dose) of CTV_{eval} were reduced by ~4 cm³ in the OD plans compared with in the PD1 plans (4 MV: mean, 3.8 cm³, range, 0.2–7.7 cm³; 6 MV: mean, 3.6 cm³, range, 1.6–6.4 cm³), and the V_{47.5 Gy} values (47.5 Gy was 95% of prescribed dose) by ~2 cm³ (4 MV: mean, 1.7 cm³, range, 0.8–3.5 cm³; 6 MV: mean, 1.7 cm³, range, 0.9–2.6 cm³). No significant differences in these reductions were observed between plans using 4 MV and 6 MV for V_{50 Gy}, V_{49 Gy}, V_{47.5 Gy}, and V_{45 Gy} (P = 0.495, 0.879, 0.782 and 0.610). The minimum dose (D_{min}) of CTV_{eval} in the OD plans using 6 MV was reduced by ~5% compared with that in the PD1 plans (mean, 4.6%; range, 1.3–7.8%). The reduction was significantly larger in the 4 MV OD plans than in the 6 MV OD plans (mean, 8.2%; range, 6.2–11.1%; P < 0.001).

DISCUSSION
This study confirmed that X-rays were greatly attenuated after passing through the metallic port. In the down-perpendicular orientation, the attenuation rate was limited to within a few percent, with no substantial changes observed in the PDD_{100}, although the attenuation exceeded 5% in some shallow areas at 4 MV. In the up-parallel orientation, the maximum dose difference exceeded 30%, with the PDD_{100} also varying significantly. This may have been because the low energy components of the X-rays were reduced by passing through the relatively long distance of the vertically orientated metallic port, which in turn caused beam hardening and altered the slope of the attenuation curve. Accordingly, the maximum difference between the dose with the metallic port and the dose without it was observed in the shallow areas in the vicinity of the peak depth. The maximum difference was ~40% at 4 MV and ~30% at 6 MV. The value at 6 MV was almost the same as that found in two previous reports that used either a thermoluminescent dosimeter or a diode [4, 5]. Although there has been no previous study at 4 MV, it is expected that a similar level of dose measurement accuracy was obtained by the film method.

When CT imaging that captures the metallic implants is used for treatment planning, the implants are generally excluded from the irradiation field. During PMRT, however, a metallic port is inevitably included in the irradiation field in all patients other than those whose...
TTE has been replaced with an implant. Considering the uncertainty in the CT values, many institutions calculate the dose by tentatively substituting a density of 1 g/cm$^3$ in the CT slices with metallic artifacts. However, the dose distribution calculated by this method may differ strikingly from the actual measurements, particularly when the X-ray energy is low. It is imperative to establish a method that enables the accurate calculation of dose distribution during PMRT while a TTE is inserted.

Because it is not feasible to determine the density values consistent with actual measurements at every depth, most currently available RTPSs are incapable of accurately calculating changes in energy caused by a metallic material. No previous studies have proposed a method for determining the density to be allotted to a metallic port that takes into account the target depth. In the present study, we established the most likely range of target depth from CT images of actual patients and identified the optimum physical density at which the measured and calculated values were most consistent with each other within that range. A previous report calculated the most appropriate electron density as 11.8 by using the analytical anisotropic algorithm of Eclipse™ (Varian Medical Systems, Inc., Palo Alto, CA, USA) [9]. In the present study, we used the collapsed cone convolution algorithm of Pinnacle3 to estimate the optimum physical density to be 9.8 g/cm$^3$, which yielded the best fit with the actual measurements. Pinnacle3 has a preregistered table of mass attenuation coefficients for each energy level (a $\mu/\rho$ look-up table) and performs dose calculations by applying the mass attenuation coefficient for the relevant material based on the physical density of the voxels. For example, if a nominal physical density of 8.4 g/cm$^3$ (the mass attenuation coefficient of iron) is applied by Pinnacle3 to the metallic port, the percentage depth dose may be underestimated because of the attenuation caused by the port. Conversely, applying a physical density of 11.8 g/cm$^3$ (the mass attenuation coefficient of lead) to the metallic port could result in an overestimate. The application of our values, however, makes it possible to evaluate a nearly accurate dose distribution on the RTPS for patients with a TTE.

We consider that it is best to follow the procedure described in this

Fig. 6. Example of the dose distribution in post-mastectomy radiation therapy with the metallic port assigned the optimum density value. (a) 4 MV (b) 6 MV.

| Parameter | 4 MV plans | 6 MV plans | $P$ |
|-----------|------------|------------|-----|
| $V_{50\text{ Gy}}$ | $-3.8 \pm 2.0 \text{ cm}^3 \ [-0.2 \text{ to } -7.7]$ | $-3.6 \pm 1.4 \text{ cm}^3 \ [-1.6 \text{ to } -6.4]$ | 0.495 |
| $V_{49\text{ Gy}}$ | $-3.0 \pm 1.1 \text{ cm}^3 \ [-1.2 \text{ to } -5.4]$ | $-3.0 \pm 0.9 \text{ cm}^3 \ [-1.9 \text{ to } -4.8]$ | 0.879 |
| $V_{47.5\text{ Gy}}$ | $-1.7 \pm 0.6 \text{ cm}^3 \ [-0.8 \text{ to } -3.5]$ | $-1.7 \pm 0.6 \text{ cm}^3 \ [-0.9 \text{ to } -2.6]$ | 0.782 |
| $V_{45\text{ Gy}}$ | $-0.3 \pm 0.3 \text{ cm}^3 \ [-0.0 \text{ to } -0.9]$ | $-0.3 \pm 0.2 \text{ cm}^3 \ [-0.0 \text{ to } -0.9]$ | 0.610 |
| $D_{\text{min}}$ | $-8.2 \pm 1.4 \% \ [-6.2 \text{ to } -11.1]$ | $-4.6 \pm 1.6 \% \ [-1.3 \text{ to } -7.8]$ | <0.001 |

Values are presented as mean ± standard deviation [range]. CTVeval = clinical target volume for the evaluation, OD plans = plans based on the calculated optimum density, PD1 plans = plans with the metallic port assigned the physical density of 1 g/cm$^3$, V = volume, $D_{\text{min}}$ = minimum dose.
study for the set of conditions at each facility (i.e. RTPS, algorithm and X-ray energy). However, if there is no large difference in the conditions compared to those described in this report, one option is to apply a physical density of 9.8 g/cm³ for the collapsed cone convolution algorithm of Pinnacle.

Dose calculations for PMRT planning were performed with the optimum physical density used for the metallic port regions. Cold spots due to the metallic port were detected in the target volume in all optimum physical density plans compared with in the plans calculated with the value for water (1 g/cm³) used for the TTE: the volumes of the underdosed regions were ~4 cm³ at 100% of the prescribed dose and ~2 cm³ at 95% of the prescribed dose. In addition, the minimum dose in the target volume was reduced by ~8% in the 4 MV plans and by ~5% in the 6 MV plans. The clinical impact of this dose reduction is unknown and will need to be clarified in future studies. We consider that 6 MV is preferable to 4 MV for PMRT with TTE from the viewpoint of the minimum dose in the target volume. However, for very high energies, the decrease in the surface dose with increased energy is a trade-off, except when using a bolus. In that case, it would be reasonable to perform intensity-modulated radiation therapy (IMRT) instead of raising the beam energy.

When a dose distribution is evaluated with a density value allocated for a metallic port, the presence of metallic artifacts can make it difficult to identify the port accurately. Because X-rays are greatly attenuated by the port, it is essential to accurately represent its shape. Improving the accuracy of dose calculations requires the development of new technologies to allow the shapes of metallic ports to be represented more precisely, for example, by reducing metallic artifacts. Implementing metal artifact reduction techniques (e.g. dual-energy CT or algorithms) may be useful when planning CT for PMRT patients with a TTE [12–15]. Accordingly, accurate contouring and the method described in this report for determining the appropriate density for the metallic port may lead to better PMRT planning to compensate for dose reduction by adapting technologies such as IMRT or intensity-modulated proton therapy [16, 17].

Commercially available RTPSs are limited in their geometric resolution capability for depicting the contours of objects, despite the accurate shapes and arrangements of metallic objects represented on CT images. Alternatively, when a commercially available RTPS is used to perform dose calculation in high-density areas, the resolution capability of the CT value–density conversion tables may decrease in the density range of the normal human body; care should therefore be taken in such cases. Robust planning could be achieved by using IMRT, taking into account the residual uncertainty as described in this report, as well as respiratory movement.

In conclusion, it is imperative to establish a method that enables the accurate calculation of dose distribution while a TTE is inserted during PMRT. This study identified a useful method for determining the appropriate density to use in the commercially available RTPSs, taking into account the distance between the metallic port and the targets.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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