Adaptive radiotherapy dosimetry in a challenging geometry: A model gas-filled tissue expander in a helical TomoTherapy beam

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Abstract. Helical TomoTherapy treatment and delivery systems (Accuray Inc, Sunnyvale, USA) allow off-line adaptation of radiotherapy treatments, with dose calculations that use MV computed tomography (CT) data acquired at treatment. This study aimed to assess the potential dosimetric effects of a gas-filled temporary tissue expander (TTE) on the accuracy of breast radiotherapy dose calculations from both the TomoTherapy treatment planning system (TPS), which uses kV CT data, and the TomoTherapy adaptive radiotherapy (ART) system, which uses MV CT data. A TomoTherapy treatment plan was created and delivered to a 3D-printed rectilinear model of a breast with implanted gas-filled TTE, including a stainless steel CO₂ container, and film measurements of the delivered dose were compared against dose calculations from the TPS and ART systems. The film measurements showed that the TomoTherapy TPS provided comparatively accurate dose calculations in the ~550 cm² volume of air that modelled the gas filling of the TTE and within the surrounding tissue-equivalent materials, except in regions where the beam was transmitted through the stainless steel CO₂ container, possibly due to the volume of stainless steel being over-estimated in the kV CT images that were used to generate the treatment plan. The ART system provided more accurate dose calculations than the TPS in regions affected by the stainless steel container, but also over-estimated the dose in the air within the TTE. These results suggest that the TomoTherapy TPS and ART systems could be used to produce reliable dose calculations of breast treatments in the presence of gas-filled TTEs, if kV CT imaging options are chosen to avoid artefacts and minimise the need for density overrides and if treatment targets that include only clinically relevant tissues, and exclude all TTE components, are used to evaluate and compare the doses calculated by both systems.

1. Introduction
The Accuray Hi-Art helical TomoTherapy (HT) system (Accuray Inc, Sunnyvale, USA) allows off-line adaptive radiotherapy, by re-calculating treatment doses on patient MV computed tomography (CT) images acquired at treatment delivery and comparing the results against the planned treatment doses calculated initially using planning kV CT images [1-3]. This method allows efficient identification of and adaptation to the dosimetric effects of changes in patient contour, target size or treatment setup [3].

A secondary advantage of the use of MV CT data to verify dose distributions planned using kV CT data is the low susceptibility of MV CT images to reconstruction artefacts from high-density
implants [3]. However, MV images also provide reduced bone-tissue contrast compared to kV images [4] and MV CT are often optimized to limit patient dose by allowing increased noise [2]. This can mean that the intrinsic differences between kV treatment planning images and MV treatment verification images, in terms of contrast, noise and artefacts, can result in ambiguity and confusion when interpreting the results of adaptive radiotherapy dose comparisons: When results differ, especially in the presence of density heterogeneities, which system should be trusted?

Due to the precipitous density heterogeneities that result from their particular structure and function, gas-filled temporary tissue expanders (TTEs) were selected for investigation in this study, as a useful worst-case-scenario. TTEs are used in two-stage breast reconstructions, after mastectomies for breast cancer [5,6]. Breast TTEs are usually filled with saline via a magnetic port [5] but can be filled with CO₂ via a metallic gas canister located within the implant [6]. Gas-filled TTEs are therefore expected to detrimentally affect the accuracy of radiotherapy treatment dose calculations due to the presence of a high-density (mostly stainless steel) component, within a large low-density (gas) volume, covered by a thin layer of skin and residual breast tissue. Previous studies have shown how such implants can affect static photon beams [7,8] and electron beams [9], but effects on TomoTherapy dose calculations and MV CT-based adaptive radiotherapy dose calculations have not been reported.

This study used multi-plane film measurements to evaluate the accuracy of dose calculations provided by both the TomoTherapy “Hi-Art” treatment planning system (TPS) and the TomoTherapy “Planned Adaptive” adaptive radiotherapy (ART) dose re-calculation and evaluation system. A model gas-filled TTE was developed, to provide a rectilinear but realistically heterogeneous test object, for evaluating the performance of the TomoTherapy TPS and the ART systems under geometrically and dosimetrically challenging conditions that were similar to the treatment of a breast radiotherapy patient with a gas-filled TTE.

2. Method and materials

Previous studies of the effects of gas-filled TTEs on the dose from breast radiotherapy treatments have compared TPS dose calculations for static tangent beams against point dose measurements on humanoid phantoms with sample TTEs [7,8] or on the skin of a patient with a TTE in situ [10]. To provide additional information on the dose in and around gas-filled TTEs, while providing two-dimensional dose measurements appropriate for evaluating a modulated radiotherapy beam [11], a simple phantom geometry was constructed using an additive deposition 3D-printing technique.

The 3D-printed components of the phantom were designed using TinkerCAD software (Autodesk Inc, San Rafael, USA), to house a stainless steel CO₂ container and a ~550 cm² volume of air, approximately modelling a 0.5 – 1.0 cm thick layer of tissue covering a gas-filled TTE (see figure 1(a)). This simulated “breast tissue” was designed to be rectilinear and printed in two halves, to allow film measurements within the model implant that could be unambiguously compared against dose calculations provided by the TPS and ART systems. An Ultimaker 2 Extended+ 3D printer was used to
fabricate the model, using PLA filament, with a 90% in-fill density. This material and density were chosen due to their established radiological tissue-equivalence [12].

The 3D-printed breast model, containing the CO2 container and pieces of Gafchromic EBT3 radiochromic film, was positioned on top of a 30 × 30 × 10 cm3 slab of Virtual Water (Standard Imaging Inc, Middleton, USA), with a small piece of bolus placed on top of the breast at the location where a mastectomy scar would occur, duplicating local clinical procedure. This setup (shown in figure 1(b)) was used during acquisition of kV CT image data (used for treatment planning), as well as during acquisition of pre-treatment MV CT image data (used for treatment setup verification and ART dose calculation) and during treatment delivery. More than 20 h after treatment delivery, the film was scanned and results were converted to dose [11] before being compared with dose calculations from the TomoTherapy TPS and ART systems.

3. Results and discussion

The kV CT of the phantom was observed to be affected by image reconstruction artefacts, arising from the presence of the metallic CO2 container within the model breast. The affected regions of the kV CT were therefore contoured and over-ridden with realistic density values, for air, water and stainless steel, before treatment planning. The MV CT of the phantom, acquired at treatment, was observed to be noisier than the kV CT but unaffected by artefacts, so no overrides were applied before dose calculation by the ART system.

Figures 2(a)-(d) show the results of film measurements at various locations within the phantom and demonstrate the effects of the model gas-filled TTE on the accuracy of dose calculations provided by the TPS and ART systems.

![Figure 2](image.png)

*Figure 2.* Film results (solid line) compared with dose calculations from TPS (circles) and ART system (crosses): (a) longitudinal profiles on top of Virtual Water, directly beneath the 3D-printed breast, (b) longitudinal profiles within Virtual Water, 5 cm posterior of the 3D-printed breast, (c) transverse profiles (anterior-posterior) through the centre of the 3D-printed breast, and (d) lateral profiles through the centre of the 3D-printed breast.
Figure 2(a) illustrates how the treatment planning system achieved a homogeneous dose profile in the tissue-equivalent material directly beneath the model breast, by increasing the photon fluence through the metallic component of the implant. Figure 2(a) also shows that the TPS apparently over-estimated the beam attenuating effect of the metal CO$_2$ container (through the central ± 1.0 cm of the profile), with both the film measurement and the ART calculation showing doses greater than the TPS-calculated dose in this region. Similar results, with the film measurement and the ART calculation both exceeding the TPS-calculated dose in the region where the beam is transmitted through the metal CO$_2$ container, are apparent even in the approximately tissue-equivalent material 5 cm posterior to the model breast (figure 2(b)). These results were likely caused by the TPS over-estimating the beam attenuating effect of the stainless steel CO$_2$ container due to the kV CT images showing the container as larger than its true physical size [13]. This apparent geometric difference may have been as large as 0.2 cm in all directions [13], which sums to 0.8 cm in the anterior-posterior direction, for this hollow gas container.

Figures 2(c) and (d) show profiles that were measured and calculated in a transverse plane, within the 3D-printed model of the breast and TTE. These results indicate that the TPS provides a more reliable indication of the dose throughout the gas inside the implant, with the ART calculation noticeably exceeding the dose calculated by the TPS and measured using film. The disagreement between the ART calculation and the TPS calculation increases in regions closer to the CO$_2$ container, possibly due to increasing levels of noise (appearing as localized density variations) within the MV CT image that was used by the ART calculation.

4. Conclusions
In tissue-equivalent media downstream of the implant, there was comparatively good agreement between the measured and calculated dose distributions, except in regions where the dose distribution was affected by the stainless steel CO$_2$ container, where the TPS calculation may have over-estimated the volume occupied by stainless steel. It should be possible to avoid this discrepancy through the use of an extended CT range and a metal artefact reduction algorithm when reconstructing kV CT images of gas-filled TTEs, to minimize imaging artefacts and reduce reliance on density over-rides.

By contrast, film measurements showed that the TomoTherapy TPS provided a more accurate calculation of dose within the air inside the model TTE, with the TomoTherapy ART system over-estimating dose in this region. For each patient with a gas-filled TTE, it is therefore advisable to contour an additional treatment target, which includes only the patient’s targeted tissues and excludes all parts of the implant, for use when evaluating and comparing the results of TPS and ART dose calculations.

If the above two precautions are carefully applied, then it should be possible to achieve and act upon accurate dose calculations from the Tomotherapy TPS and the TomoTherapy ART system, when delivering adaptive radiotherapy treatments to patients with gas-filled TTEs.

5. References
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