

Clinical Significance Of Air Bubbles In Breast Balloons For The Xoft 50 kV Brachytherapy Source Determined By TG-43 And MCNP Modeling

Randall W Holt, PhD,^{1,2} and John J DeMarco, PhD³

¹Pacific Crest Medical Physics, Chico, CA; ²Xoft, Inc, Sunnyvale, CA; ³UCLA, Radiation Oncology, Los Angeles, CA

ABSTRACT

Purpose: To examine the effect on the dosimetry above a residual air bubble in a breast balloon when treating with the Xoft Axxent® 50 kVp electronic brachytherapy source. The Xoft Axxent® 50 kVp electronic brachytherapy source has been well characterized in water (Rivard, et al). When inflating a balloon with water, it may be possible for residual air to remain in the balloon. A first order approximation of the effect of an air bubble was made using TG-43 parameters and Monte Carlo modeling (MCNPX).

Materials and Methods: A 20 mm radius balloon with a single central dwell point was modeled using TG-43 parameters and with MCNPX. The dosimetric effects of a reduction of attenuation can be modeled by shifting the depth parameter in the radial dose function, $g(r)$, by the height of the bubble, using $r' = r - \text{bubble height}$. The MCNPX Monte Carlo code was used to simulate the same configuration with and without a 5 mm thick air bubble for the same geometry. The effect of a more typical linear train of sources at non-central dwell points was also examined using the TG-43 model. For this clinical plan model, the source catheter axis was assumed to be parallel to the air-bubble, and used nine dwell positions, spaced 5 mm apart. To mimic the shape of the air bubble in the top of the balloon, it was assumed that the diameter of the bubble was twice the height of the air bubble.

Results: For a single central dwell point, the relative increase in dose due to an air bubble as modeled by TG-43 is shown in figure 1 as a function of air bubble height. For a 5 mm tall air bubble, the dose is predicted to increase by 23%, 18% and 15% at the surface, 5 mm above the surface and 10 mm above the surface, respectively. Using MCNPX, increases of 22%, 20.5 and 18% were computed (also in figure 1). For a plan with multiple dwell points, the effect is decreased for smaller bubbles. X-rays from off-center dwell points which pass through a small bubble will not contribute to enhanced dose at the reference points. For multiple dwell points, a 1 mm bubble would increase dose by less than 3.8%, 0.7% and 0.6% at 0 mm, 5mm and 10 mm above the balloon surface. An air-bubble 2 mm high x 4 mm wide would increase dose by 8%, 3.5% and 3% at the same points, and a 5 mm high x 10 mm wide air bubble would increase dose by 23%, 18% and 12% respectively.

Conclusions: The presence of an air bubble in a balloon for a Xoft electronic brachytherapy treatment will result in an increase of dose that is not accounted for during patient planning. Modeling this dose increase by using a shifted radial dose function is supported by the MCNPX model results; although the shifted TG-43 model underestimates the overall effects at 10 mm above the balloon surface for a 5 mm tall air bubble. With consistent daily patient positioning, it is likely that the air bubbles will be at or near the same location for each treatment. These results indicate that small residual air bubbles in the Xoft APBI balloon of less than 2 mm tall x 4 mm in diameter would have a negligible or minor overall effect to a treatment plan. Residual air bubbles between 3 and 4 mm tall x 6-8 mm wide could have an impact on the skin dose, and should either be removed, reduced, or dosimetrically evaluated for the individual patient plan to verify that the skin dose does not exceed acceptable limits. Residual air bubbles of greater than 4 mm in height and greater than 8 mm in diameter should be removed or reduced during the CT simulation and dosimetry planning and evaluation steps.

INTRODUCTION

The Axxent® Electronic Brachytherapy (eBx) System has been in clinical use for over three years, delivering accelerated partial breast irradiation (APBI) using a balloon placed into the patient's resection cavity post-lumpectomy using a miniature x-ray source (Figure 1).

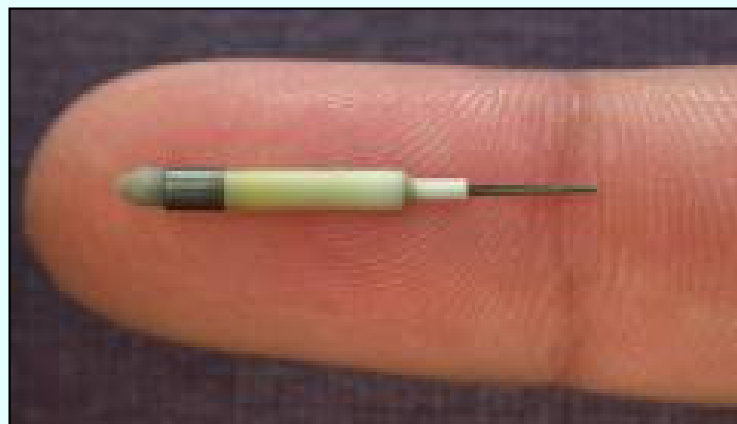


Figure 1. Miniature x-ray source, 50 kV, courtesy, Xoft, Inc.

The instructions for use of the Xoft Axxent® Breast Balloon for APBI treatments with the Xoft Axxent® 50 kVp source state that the residual air in the balloon should be removed prior to insertion. This can be accomplished by inflating the balloon with sterile saline, prior to insertion, and then deflating the balloon, and removing any residual air at the same time. While this method is simple to accomplish, a very small amount of residual air may remain in the balloon.

The Xoft source emits average energies of x-radiation between 26 and 32 kVp. The deposition of this radiated dose has been well characterized in water (Rivard, et al). When using this type of dose model, it is assumed that the photons are always traveling through a near water-equivalent media. If the photons were to travel through some regions of air in the balloon, it might be expected that the planned dose would underestimate the actual dose in some areas, as the photons would not be normally attenuated as they would in water. Small bubbles might have a minimal effect, and could be tolerated, where larger air volumes might result in clinically intolerable doses above the air bubble.

The dose deposition in the presence of air bubbles in a balloon are investigated here in order to provide guidance on determining what size limits of residual air bubbles could be clinically tolerated.

MATERIALS AND METHODS

MCNPX MODEL

The MCNPX Monte Carlo code was used to simulate the effects of an air bubble in an otherwise homogenous balloon (Figure 2). Calculations were conducted both with and without a 5 mm thick air bubble for the same geometry.

TG-43 METHOD FOR HETEROGENOUS CALCULATIONS

A first order approximation of the effect of an unintentional air bubble in the balloon can be made using the TG-43 parameters. A more rigorous simulation can be made using the MCNPX Monte Carlo method. For the first order TG-43 method, the dosimetric effects of a reduction of attenuation can be modeled by shifting the depth parameter in the radial dose function,

$$g(r) \rightarrow g(r'), \text{ where}$$

r is the distance from the source to the calculation point,

r' is the effective depth the photons traverse, and

$$r' = r - \text{bubble height.}$$

As all other parameters of the TG-43 dose calculation are unchanged, the change to the predicted dose can be computed from the radial dose function, $g(r)$, as

$$\text{Relative Dose Change} = g(r') / g(r)$$

For ease of computation, the radial dose function, $g(r)$, can be modeled as the sum of two exponentials, with good agreement (+/- 2.5%) over the range of 10 to 50 mm distance, where the function (Figure 3) is

$$g(r) = 1.06 * (r/10)^{-0.6} - 0.06 * (r/10)^{-0.38}$$

BALLOON GEOMETRY FOR SINGLE DWELL POINTS

For this study, a 20 mm radius balloon was examined (Figure 4), with 3 representative calculation points: surface, 5 mm above the surface and 10 mm above the surface.

OFF CENTER DWELL POINTS (Figure 5)

Gravity, surface tension, the volume of the bubble and the radius of the balloon will also create a complex relationship between the air bubble volume, height and width. For this model, these factors have been simplified to assume that the air-bubble width is equal to twice the air-bubble height.

For very small air bubbles, off-center sources may not intersect the air bubble and will have negligible effect (→). For a source not at the center of the balloon, the oblique path will elongate the length of the air path (→→). This relationship was further investigated using the TG-43 model.

MULTIPLE DWELL POINTS (Figures 6 and 7)

Typical clinical plans will also be weighted, such that the more central sources will have more effect on the dose than peripheral sources. Nine dwell positions, spaced 5 mm apart were used for this model. The effects of various bubble sizes were examined using the TG-43 model for a typical case, for a 20 mm radius balloon. It was assumed that the source catheter axis is parallel to the air-bubble.

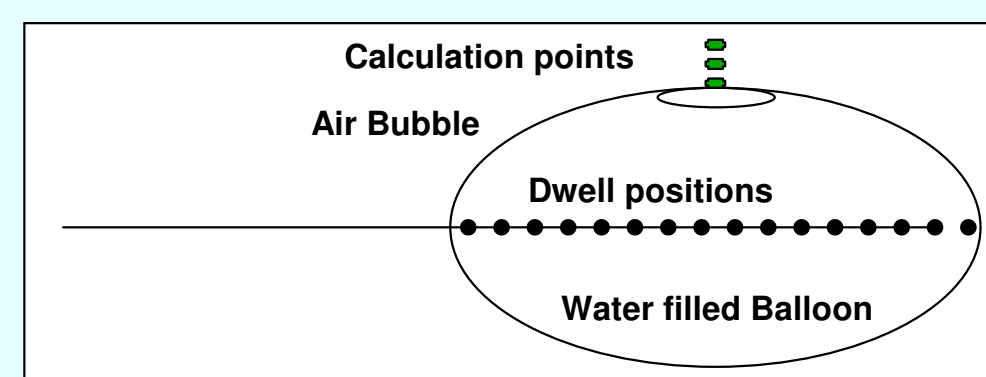


Figure 6. Inclusion of multiple dwell positions in the typical balloon treatment.

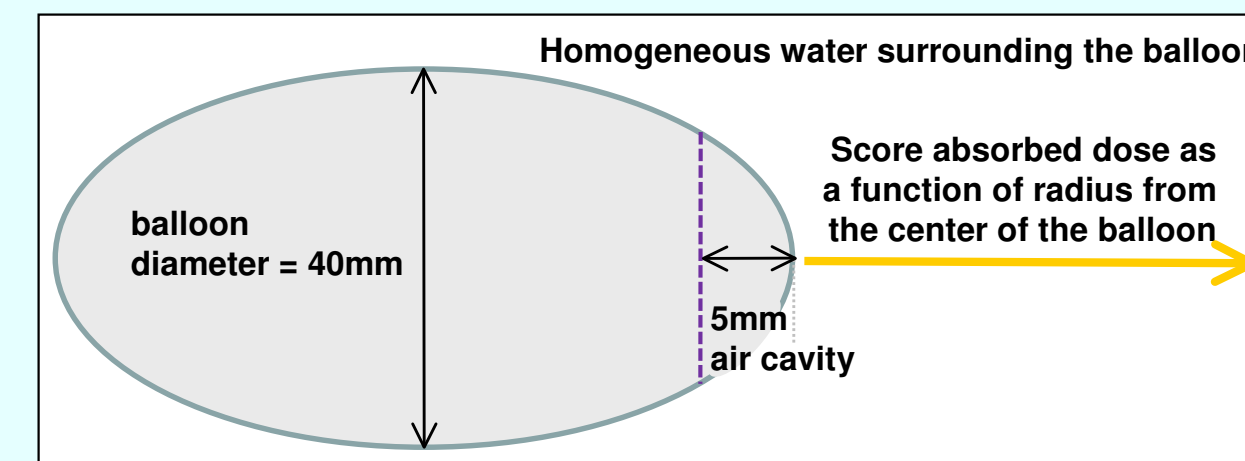


Figure 2. Balloon Geometry of the MCNPX model, including bubble sizes and calculation points

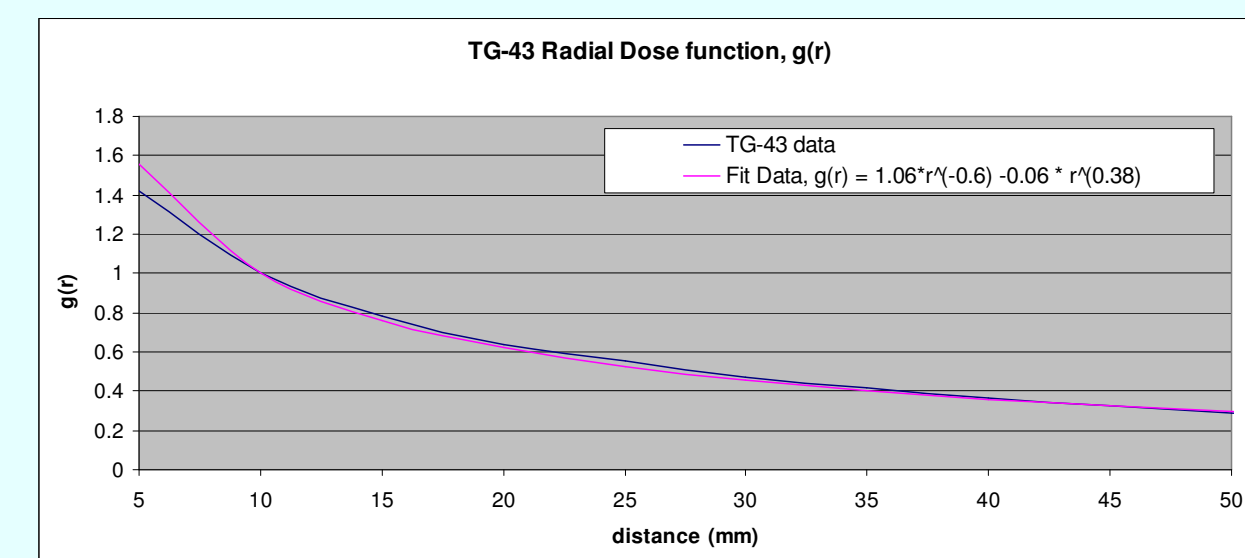


Figure 3. Xoft 50 kV Radial Dose function, modeled with 2 exponentials

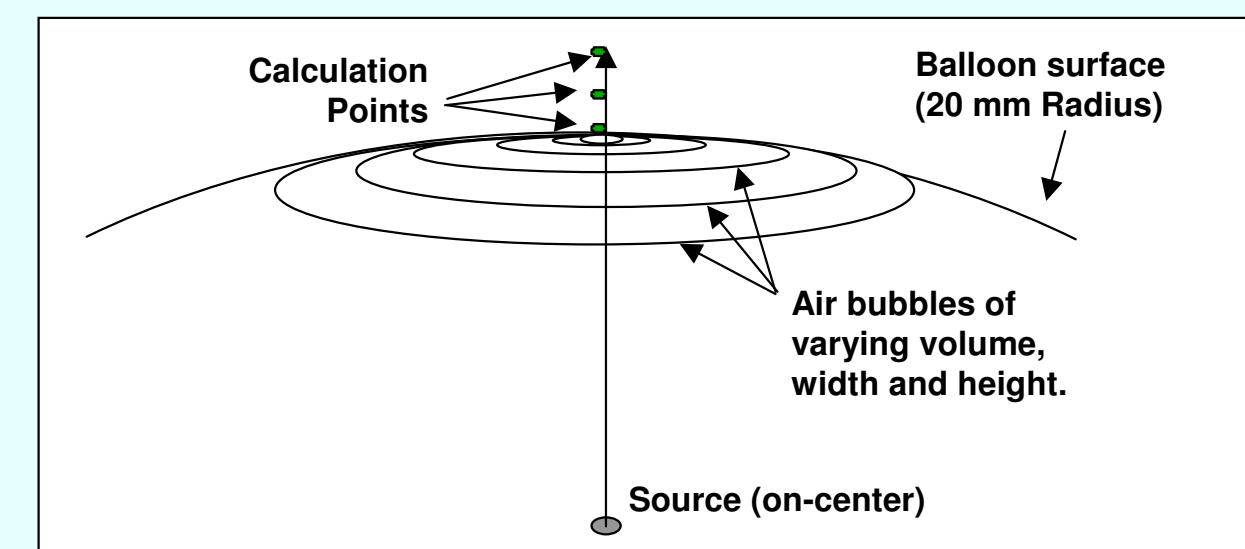


Figure 4. Balloon Geometry, including bubble sizes and calculation points

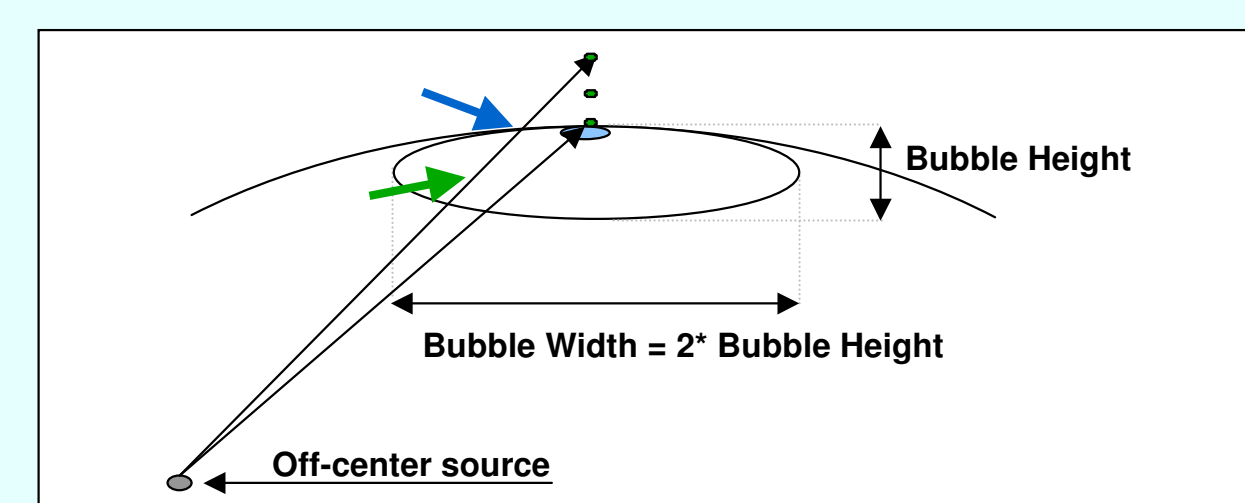


Figure 5. Including the effect of the oblate spheroid geometry of the bubble in a balloon.

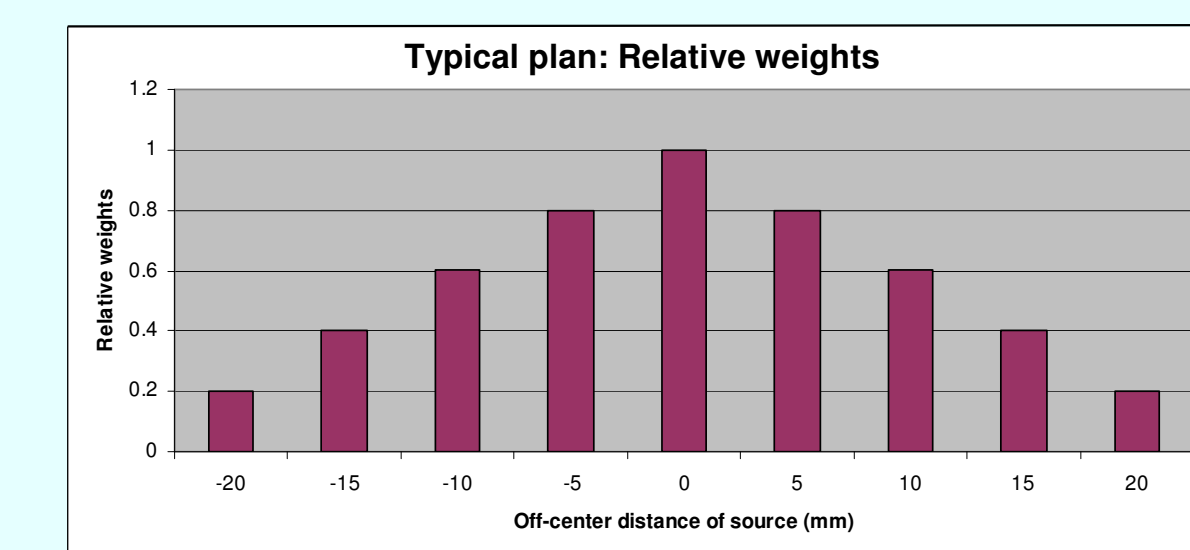


Figure 7. Typical weighting for a multiple dwell point plan.

RESULTS

MCNPX MODEL

Using MCNPX, an increase of 22% in the dose at the surface would be expected from a 5 mm air bubble (Figure 8), tapering off to 18% at the typical prescription point at 1 cm.

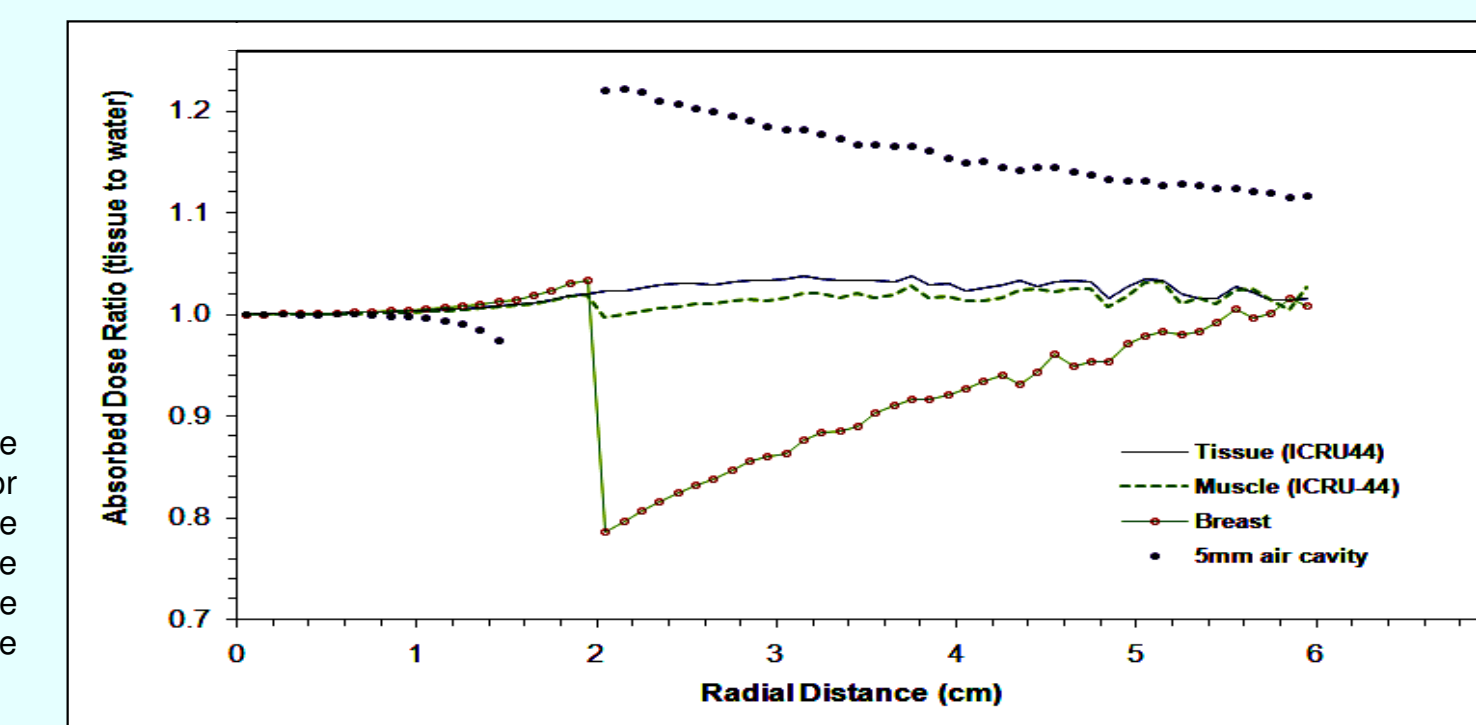


Figure 8. The MCNPX model for a 5 mm air bubble relative to the expected dose are shown by the purple dotted line.

TG-43 SINGLE POINT MODEL

For a single central dwell point, the relative increase in dose due to an air bubble as modeled by TG-43 is shown in Figure 9 as a function of air bubble height. For a 5 mm tall air bubble, the dose is predicted to increase by 23%, 18% and 15% at the surface, 5 mm above the surface and 10 mm above the surface, respectively. The MCNPX points at 5 mm above the surface are also noted in Figure 9, with increases of 22%, 20.5 and 18%.

TG-43 OFF-AXIS SINGLE POINT MODEL

As noted in Figures 10(a and b) the increase of the path length through the bubble for non-centered dwell points will increase the dose at the calculation point only slightly compared to a central source, less than 3% for a 10 mm air bubble for a calculation point located on the surface directly above the balloon.

At calculation points 10 mm above the surface, off center distances contribute less to the dose enhancement. With this simplified TG-43 model, a 5 mm high x 10 mm wide air bubble will not interfere with dose deposition for sources located 20 mm from the center of the balloon.

TG-43 MULTIPLE DWELL POINT MODEL

As noted in Figure 11, for a plan with multiple dwell points, the overall dose enhancement effect is decreased for smaller bubbles, as X-rays from off-center dwell points which pass through a small bubble will not contribute to enhanced dose at the reference points. For multiple dwell points the radial dose function shifted TG-43 model shows that:

- 1 mm high x 2mm wide bubbles would increase dose by less than 3.8%, 0.7% and 0.6% at 0 mm, 5 mm and 10 mm above the balloon surface.
- 2 mm high x 4 mm wide air bubbles would increase dose by 8%, 3.5% and 3% at the same points.
- 5 mm high x 10 mm wide air bubbles would increase dose by 23%, 18% and 12% respectively.
- 7 mm high x 14 mm wide air bubbles would result in 35% more dose at the balloon surface and 23% more dose at 10 mm from the surface.

Conclusions

- Small residual air bubbles in the Xoft APBI balloon of less than 2 mm tall x 4 mm in diameter would have a negligible overall effect to a treatment plan.
- Residual air bubbles between 3 and 4 mm tall x 6-8 mm wide could have an impact on the skin dose, and should either be removed, reduced, or clinically evaluated for the individual patient plan to verify that the skin dose does not exceed acceptable limits.
- Residual air bubbles of greater than 4 mm in height and greater than 8 mm in diameter should be removed or reduced during the CT simulation and dosimetry planning and evaluation steps.
- The TG-43 shift method was confirmed using the MCNPX model to be acceptable for a first order approximation of the dose above an air bubble in a balloon.

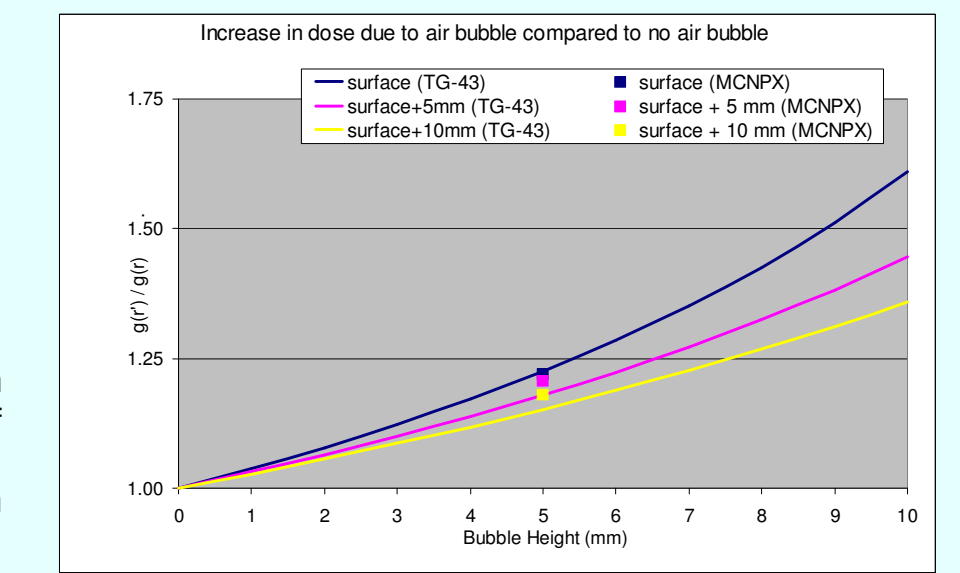


Figure 9. The increase in dose as a function of bubble height is shown at the surface, 5 mm and 10 mm locations.

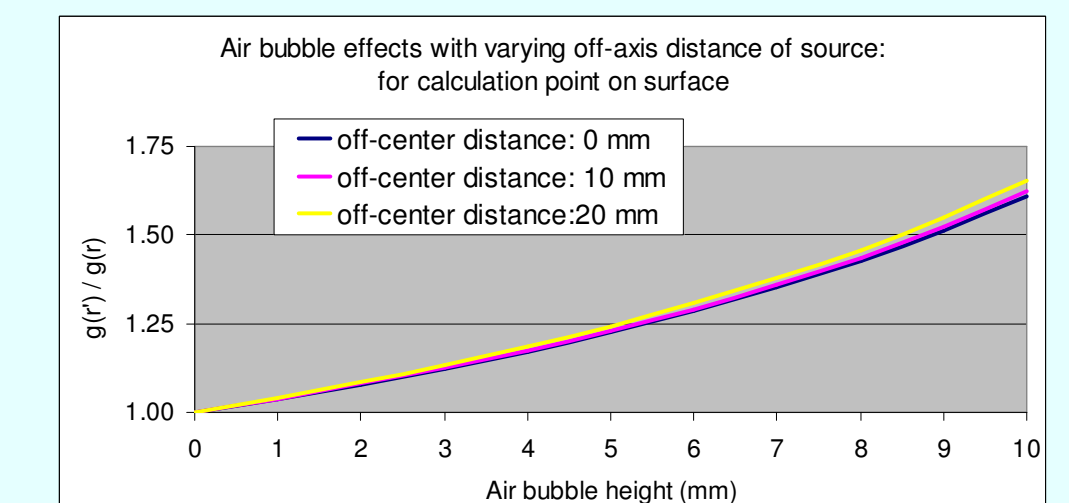
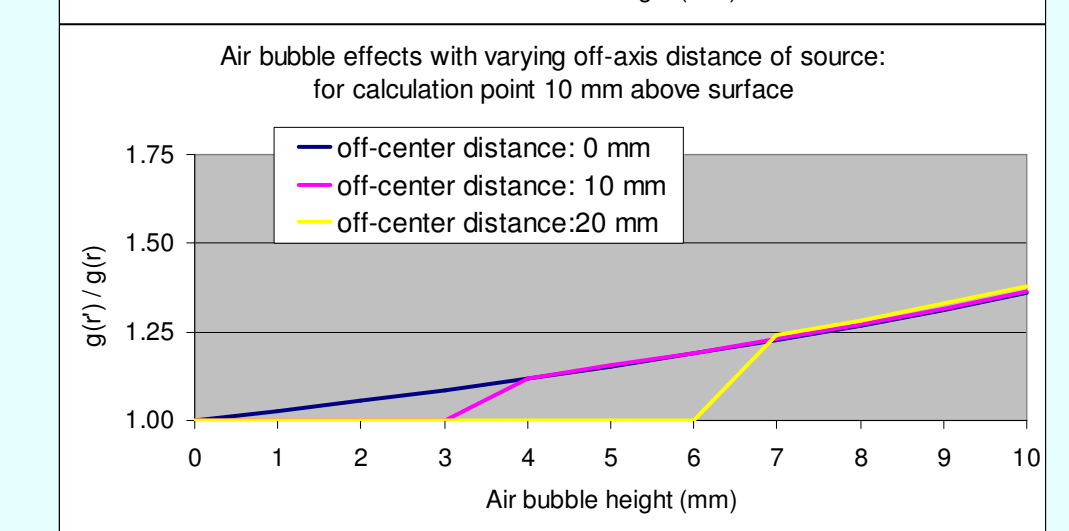


Figure 10. The increase in dose with air bubble height and with varying off center distances of the source dwell position is shown:



(a) for a point on the surface of the balloon directly above the bubble; and (b) for a point 10 mm above the surface of the balloon directly above the bubble.

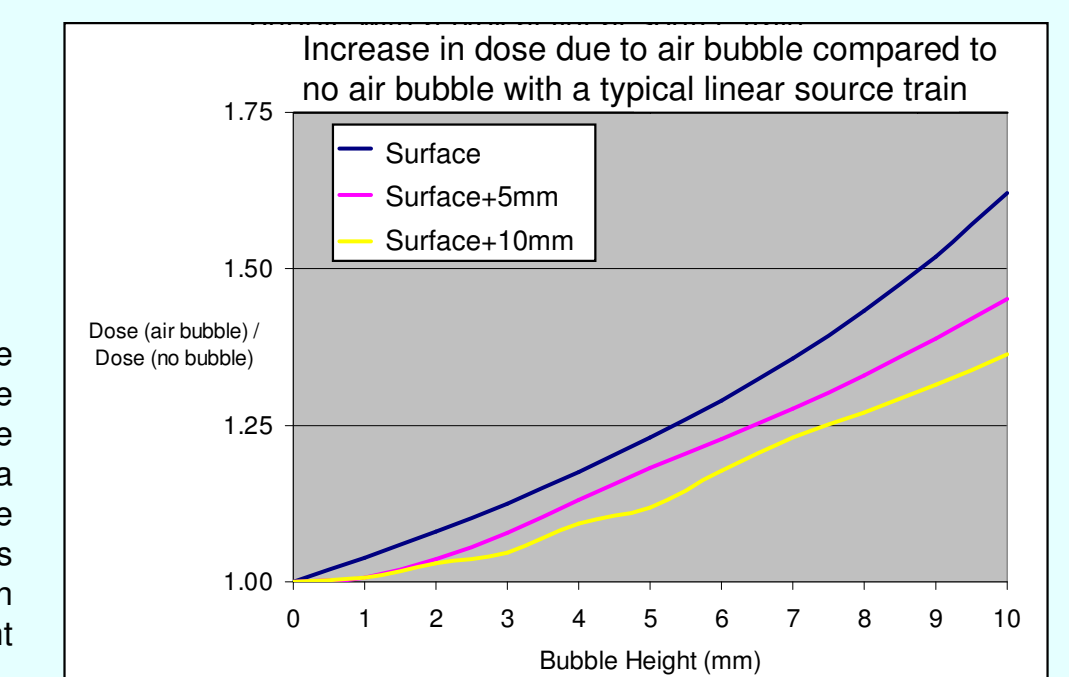


Figure 11. The increase in dose with air bubble height for a typical multiple dwell point plan is shown for each calculation point location.