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Technical Note

Dosimetric effects of saline- versus water-filled balloon applicators for IORT using the model S700 electronic brachytherapy source

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ABSTRACT

PURPOSE: The Xoft Axxent Electronic Brachytherapy System (Xoft, Inc., San Jose, CA) is a viable option for intraoperative radiation therapy (IORT) treatment of early-stage breast cancer. The low-energy (50-kVp) X-ray source simplifies shielding and increases relative biological effectiveness but increases dose distribution sensitivity to medium composition. Treatment planning systems typically assume homogenous water for brachytherapy dose calculations, including precalculated atlas plans for Xoft IORT. However, Xoft recommends saline for balloon applicator filling. This study investigates dosimetric differences due to increased effective atomic number (Z_{eff}) for saline ($Z_{eff} = 7.56$) versus water ($Z_{eff} = 7.42$).

METHODS: Balloon applicator diameters range from 3 to 6 cm. Monte Carlo N-Particle software is used to calculate dose at the surface (D_s) of and 1 cm away (D_{1cm}) from the water-/saline-filled balloon applicator using a single dwell at the applicator center as a simple estimation of the dosimetry and multiple dwells simulating the clinical dose distributions for the atlas plans.

RESULTS: Single-dwell plans show a 4.4–6.1% decrease in D_s for the 3- to 6-cm diameter applicators due to the saline. Multidwell plans show similar results: 4.9% and 6.4% D_s decrease, for 4-cm and 6-cm diameter applicators, respectively. For the single-dwell plans, D_{1cm} decreases 3.6–5.2% for the 3- to 6-cm diameter applicators. For the multidwell plans, D_{1cm} decreases 3.3% and 5.3% for the 4-cm and 6-cm applicators, respectively.

CONCLUSIONS: The dosimetric effect introduced by saline versus water filling for Xoft balloon applicator–based IORT treatments is ~5%. Users should be aware of this in the context of both treatment planning and patient outcome studies. © 2017 American Brachytherapy Society. Published by Elsevier Inc. All rights reserved.

Keywords: Xoft; Electronic brachytherapy; Heterogeneity; Monte Carlo; IORT

Introduction

Breast cancer is the most commonly diagnosed cancer in women (1) and ~60% of newly diagnosed breast cancers are early stage (2). For early-stage breast cancers, breast-conserving therapy, consisting of primary tumor resection plus whole-breast irradiation with a boost to the tumor bed, is the preferred treatment (3), providing similar survival/local control and improved cosmesis compared to mastectomy (4,5). Moreover, it is postulated that most local relapses occur in the operative region (~85%) and recurrences in other quadrants are most likely new ipsilateral carcinomas (6). For certain breast cancers, this justifies intraoperative radiation therapy (IORT), delivering radiation to the tumor bed in one fraction combined with breast-conserving surgery. IORT's accelerated treatment regimen decreases likelihood of tumor cell proliferation following surgery, eliminates risk of incomplete treatment, and mitigates geographical misses. In addition, the surgical procedure allows for displacement/protection of sensitive normal structures during irradiation (7).

The portability and high-dose-rate of the Xoft Axxent kilovoltage X-ray electronic brachytherapy (eBT) modality makes it a viable breast IORT modality (7, 8). Xoft breast IORT uses a miniature 50-kVp X-ray source, placed within a balloon applicator that fills the breast lumpectomy cavity and produces dosimetrically similar treatments to other balloon-based delivery systems (9). A series of breast IORT

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clinical trials settled on a prescription of 20−21 Gy in one fraction (10,11). When delivering such high doses in a single fraction, dosimetric accuracy becomes paramount to successful outcomes. The low-energy photons (average energy ~27 keV) (12,13) increases the dosimetric role of the photoelectric effect. This interaction has a $(Z/E)^3$ dependence, potentially diminishing the accuracy of clinically assuming homogeneous water for dose calculations.

Precalculated atlas plans provided for a set of balloon sizes help streamline Xoft IORT. These are calculated assuming homogeneous water as is standard in brachytherapy treatment planning. However, the manufacturer recommends saline rather than water filling for the balloon applicator to avoid complications if it ruptures within the patient. Although present in low concentrations (9.0 g/L NaCl), the higher-Z sodium and chloride ions increase the effective atomic number (Z_{eff}) and may result in considerable differences between delivered and planned doses. The dominant physical cause is increased attenuation due to increased photoelectric interaction cross section. Spectral hardening may also be affected by balloon filling material. Until now, the dosimetric effect arising specifically from saline versus water filling has not been isolated and evaluated. We use Monte Carlo simulations to investigate and quantify the magnitude and cause of this dosimetric effect.

Material and methods

Simulation materials

The Xoft balloon applicators can be approximated as spheres (14−16). Various sphere sizes were simulated, spanning the range of clinical applicators (diameters of 3, 4, 5, and 6 cm, with 4 cm being most common). The goal was to isolate the dosimetric effect of saline balloon filling. Dosimetric effects of the silicone/barium sulfate balloon material and the source nylon catheter have been previously evaluated (17−19) and are not considered here.

In the Monte Carlo simulations, water density is 1.0 g/cm^3. The saline solution (3.54 g Na, 5.46 g Cl, 111.40 g H, and 884.20 g O) density is 1.0046 g/cm^3 (assuming temperature of 22°C and pressure at sea level) (20). The Z_{eff} for water and saline is 7.42 and 7.55, respectively, as calculated using Eq. (1), where α_i represents the relative contribution of each element to the total electrons (21,22).

$$Z_{eff} = \sqrt[2.94]{\sum_i \alpha_i \times Z_i^{2.94}} \qquad (1)$$

Source modeling

The Xoft 50-kVp source (anode size < 1 mm) was approximated as an isotropic point source (12,14,23). The input source spectrum or initial phase space is in Fig. 1 (12). Source dwell positions discussed below were simulated by moving the point source relative to the spherical balloon applicator center. Different dwell times were simulated by calculating doses with each dwell position separately and then summing these doses weighted by corresponding relative dwell times.

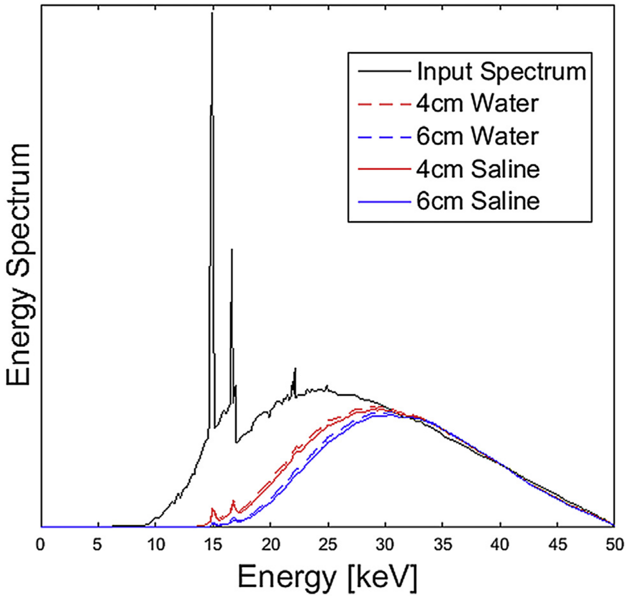

Fig. 1. Energy spectrum used in MCNP for Xoft Axxent source (input spectrum) (12) and the energy spectrum at the surface of the 4-cm (red) and 6-cm (blue) diameter balloon applicators filled with either water (dashed line) or saline (solid line). Use of saline and increase in balloon diameter both resulted in higher average photon energies at the balloon surface. MCNP = Monte Carlo N-Particle. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Simulation geometry

The source was either simulated at the applicator center or at 0.5-cm increments along the spherical applicator central axis for single-dwell and multidwell plans, respectively. Single-dwell plans provide simplified geometry for assessing physical effects of saline versus water filling. Multidwell plans provide a geometry simulating the Xoft source at actual dwell positions from clinical atlas plans.

The schematic diagram of the single-dwell plan is in Fig. 2. Spherical shell dose detection regions take advantage of the problem symmetry and increase Monte Carlo tally efficiency. The shaded central region was either water or saline. The surrounding material was water, out to a radius of 6 cm to provide backscatter.

Multidwell plans were simulated for 4- and 6-cm diameter applicators, with the five and six dwell positions of the atlas plans, respectively. These two diameters represent the most commonly used plans at our institution. A schematic diagram of the multidwell plan is in Fig. 3, with