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Development and characterization of an anthropomorphic breast phantom for permanent breast seed implant brachytherapy credentialing

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ABSTRACT

PURPOSE: To develop an anthropomorphic breast phantom for use in credentialing of permanent breast seed implant brachytherapy.

METHODS AND MATERIALS: A representative external contour and target volume was used as the basis of mold manufacturing for anthropomorphic breast phantom development. Both target and normal tissue were composed of gel-like materials that provide suitable computed tomography and ultrasound contrast for brachytherapy delivery. The phantoms were evaluated for consistency in construction (target location) and Hounsfield unit (computed tomography contrast). For both target and normal tissue, the speed of sound was measured and compared to the image reconstruction algorithm's expectation value. Five phantoms were imaged preimplant and postimplant to assess interphantom similarity as well as to evaluate the uncertainty in quantifying seed position.

RESULTS: The average Hounsfield units of the target and normal tissue gels is -146 ± 5 and 23 ± 1, respectively. The average speed of sound of the target and normal tissue gels is 1485 ± 7 m/s and 1558 ± 9 m/s, respectively, resulting in an estimated 0.4 mm uncertainty in image guidance. The registration/deformation uncertainty was determined to be 0.8 mm. The standard combined uncertainty in assessing seed position spatial accuracy, also including a 0.9 mm estimate based on literature for seed localization, is estimated to be 1.3 mm.

CONCLUSIONS: The development of the anthropomorphic breast phantom and evaluation of both the consistency as well as overall seed position uncertainty illustrates the suitability of this phantom for use in brachytherapy end-to-end delivery and implant accuracy evaluation. When evaluating a user's implant accuracy, we estimate a standard combined uncertainty of 1.3 mm.

Keywords: Anthropomorphic breast phantom; Permanent breast seed implant; Brachytherapy; Phantom characterization; Credentialing

Introduction

In 1968, the Radiologic Physics Center identified the need for consistent delivery of radiation dose to patients (1). One year later, after the National Cancer Institute began to fund the Radiologic Physics Center, a mutual goal was developed to ensure participating institutions in the National Cancer Institute–sponsored clinical trials deliver clinically comparable quality radiotherapy treatments. Almost 50 years later, all radiation therapy and diagnostic imaging quality assurance centers are integrated in a single entity, Imaging and Radiation Oncology Core (IROC) (2). The scope of IROCs radiotherapy credentialing practice extends to clinical trials under the umbrella of Radiation Therapy Oncology Group, GOG, NCCTG, and NSABP. Although not always achievable, it is customary

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Conflict of interest: Michael Roumeliotis and Tyler Meyer are shareholders and Directors of Okolo Health Inc, which is involved in the manufacture and sale of anthropomorphic breast phantoms.

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that a portion of the credentialing assessment require the participating institution to deliver radiation to a measurement device, such as a phantom or dosimeter. While the scope of credentialed trials is broad, delivery of radiation to a measurement device is currently limited to linear accelerator-based techniques, such as annual output checks or anthropomorphic phantom delivery.

Permanent implant brachytherapy credentialing via IROC is performed in clinical trials such as Radiation Therapy Oncology Group 0815. This trial's brachytherapy credentialing segment can be summarized as having two primary components: a facility questionnaire and knowledge assessment form followed by the participating institution submitting information from a recent implant (3, 4). The submission includes ultrasound (US) images, needle-loading information, pre-plan dose volume histogram and isodoses, and the post-implant treatment plan. This is a strong foundation for credentialing principles that aim to fully evaluate the participating institution's end-to-end delivery capabilities.

In 2009, the American Association of Physicists in Medicine (AAPM)'s TG137 report utilized data from 11 contributing institutions to measure outcomes for permanent prostate implant brachytherapy. While the reported data showed excellent clinical outcomes, the report itself indicated that although the analysis was not broken down by institution, not all institutions had equal success (5). These results suggest that implant quality is a factor that could lead to substantial differences in clinical outcome. Although permanent prostate implants are well-developed techniques, there are newly developing low-dose-rate brachytherapy techniques such as permanent breast seed implant (PBSI) brachytherapy (6–8) that may have similar issues. Because the delivery technique in PBSI is similar to permanent prostate brachytherapy, it stands to reason that validation of implant accuracy is important as new treatment centers adopt the technique. A comprehensive end-to-end brachytherapy credentialing process that focused on assessing a participating institution's delivery accuracy would be useful in ensuring the delivery of clinically comparable radiotherapy treatments. In this work, an anthropomorphic breast phantom is developed and characterized with the aim that the phantom be used for PBSI brachytherapy seed delivery with the capability to assess a user's implant accuracy in a credentialing process.

To demonstrate that a phantom is appropriate for end-to-end brachytherapy delivery, it must provide a medium that is deliverable, a consistent delivery experience between users, possess an appropriate speed of sound for US imaging and live user feedback, and display US and computed tomography (CT) contrast between target and normal tissue. This allows utilization of the phantom for brachytherapy delivery by simulating patient imaging, planning, and delivery. The relevant phantom characteristics are reported in this work.

For use in a credentialing context, a credentialing body requires the capability to assess the participating institution's delivery accuracy with a known or estimated uncertainty. Inherent to the evaluation process is the uncertainty with which the credentialing body can localize the delivered seed position relative to the planned seed position. This overall uncertainty in seed position is comprised of the registration and target deformation uncertainty, seed localization uncertainty, and uncertainty in the user's visualized needle position due to differences in expected and measured speed of sound in the phantom. In this work, overall uncertainty in seed position is evaluated and reported.

Methods and materials

Phantom development

The anthropomorphic breast phantom was developed using two different gels to simulate a target and normal tissue. A representative set of contours was used with a Haas TM1 computer-controlled milling machine (Haas Automation Inc, Oxnard, CA) to produce a positive, or plug, of the desired shape for the gel phantom, representing the outer breast contour and the inner chest wall contour. A carbon fiber mold of the anterior half of the breast was created with attachments to suspend the target within the mold as the gel is poured. The posterior half of the mold is a permanent plastic backing to support the gel phantom, created from a thermoplastic press to the milled plug. The gel phantom remains on this permanent backing and is critical in limiting deformation in the gel-based phantom to ensure that any change in phantom shape during transportation is minimized.

The target is created separately by using an aluminum mold. The target is representative of a medium to large-sized seroma with a total volume of approximately 15 cm^3. The suspension point within the phantom mold was chosen to be centrally located, well separated from the skin and chest wall to represent a relatively simple anatomy for implantation.

The target is composed of a synthetic ballistic gel, whereas the normal tissue is composed of a gelatin, propylene glycol, and water. Both gel-based materials were fabricated with the intent that the speed of sound closely matches the properties of the expected speed of sound in the US reconstruction algorithm. After the gel is set, the phantom is placed on a stand designed to support the permanent plastic backing so the anatomy is oriented to match the standard supine delivery. Figure 1a shows a transverse view of a CT image of the phantom, illustrating the target position relative to anterior and posterior borders. Figure 1b is a 3D rendering of the phantom illustrating both the body contour as well as the target location centrally located in the superior and inferior borders. Figure 2 shows an axial US image of the phantom.

Phantom characteristics for PBSI end-to-end use

Phantom consistency

Each of the five phantoms was imaged by CT and assessed for interphantom similarity. Quantification of phantom similarity for this purpose poses a challenge since the focus is to