Medical Dosimetry 39 (2014) 98–101

Medical Dosimetry

journal homepage: www.meddos.org

Use of proton beams with breast prostheses and tissue expanders

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ARTICLE INFO

Article history:
Received 31 August 2013
Accepted 25 October 2013

Keywords:
Proton
Breast
Prosthesis
Stopping power

ABSTRACT

Since the early 2000s, a small but rapidly increasing number of patients with breast cancer have been treated with proton beams. Some of these patients have had breast prostheses or tissue expanders in place during their courses of treatment. Procedures must be implemented to plan the treatments of these patients. The density, kilovoltage x-ray computed tomography numbers (kVXCTNs), and proton relative linear stopping powers (pRLSPs) were calculated and measured for several test sample devices. The calculated and measured kVXCTNs of saline were 1% and 2.4% higher than the values for distilled water while the calculated RLSP for saline was within 0.2% of the value for distilled water. The measured kVXCTN and pRLSP of the silicone filling material for the test samples were approximately 1120 and 0.935, respectively. The conversion of kVXCTNs to pRLSPs by the treatment planning system standard tissue conversion function is adequate for saline-filled devices but for silicone-filled devices manual reassignment of the pRLSPs is required.

Introduction

In the past, proton therapy was limited to a small subset of patients for whom conventional x-ray or electron radiation was not as successful as desired. With wider availability of equipment and more trained personnel, protons are currently being applied to a larger variety of disease sites. In the early 2000s, several clinical trials were begun for treating breast cancer with proton beams.[1-7] Some patients treated with proton beams have previously had implanted breast prostheses or tissue expanders. The materials in these implants may not have characteristics that lie on the standard tissue conversion function curve used by treatment planning systems (TPSs) to convert kilovoltage x-ray computed tomography numbers (kVXCTNs) to proton relative linear stopping powers (pRLSPs). pRLSPs are necessary to determine the required depth of penetration of a beam to treat tumors and avoid normal tissues. If the correct pRLSPs are not assigned to the various materials, geometrical misses may occur, thereby resulting in lack of tumor cure or normal tissue complications. Previous publications have described studies of the penetration of megavoltage x-ray and electron beam through such implants, but a literature search did not find any studies performed with proton beams.[8-11] This work studied the characteristics of several test samples of materials used in these implants for use in proton beam therapy.

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Methods and Materials

Composition of materials

The composition of implanted tissue expanders and prostheses varies greatly not only between manufacturers but even for a single manufacturer. Middleton[12] reported that, within the first 25 years after the silicone implant was devised, more than 240 different devices had been marketed, each with a variety of sizes and shapes. These implant devices typically consist of an outer shaping shell that touches the patient's tissues, an inner filling material that provides bulk, and typically one or more inner containment shells for added protection in case of a breach of the outer shell. The containment shells are typically made of a silicone-, polyester-, or polyurethane-based plastic but are usually less than a millimeter thick and therefore any deviation of the real pRLSP from that predicted by the TPS using the standard tissue-based kVXCTN to pRLSP conversion function has minimal effect on the beam penetration. The biggest effect on penetration is due to an error in predicting the pRLSP of the inner filling material.

The filling material for most tissue expanders and some breast prostheses is "normal saline," which consists of 9 g of NaCl per 1000 mL of distilled water, yielding a salt concentration of about 0.9% by weight. However, the composition of the filling material for silicone-based breast prostheses is quite variable. The first modern-style silicone-filled breast prosthesis was implanted in a human by Cronin and Gerow in 1962 and subsequently patented.[13] The most common filling material for silicone-based prostheses has been polydimethylsiloxane (PDMS). Some of the PDMS filling material consists of very large molecules of cross-linked polymer, which form a three-dimensional "net," while much of the filling material (up to 80% by mass) consists of low-molecular-weight polymer fluid, often with a viscosity of about 1000 cSt, which can move around and through the net.[14] This polymer network swollen with fluid yields a sticky cohesive mass without form depending upon the extent of cross-linking and how much fluid is added.[15] Other materials, such as cross-linkers and catalysts (some containing platinum or tin), generally make up less than 4% of the total filling material. Discussions of silicone-based biomaterials can be found in the report by Colas and Curtis.[16,17] The chemical structure of the monomer unit of PDMS is given in Fig. 1. For calculating the radiological characteristics of silicone implants, the filling material was assumed to be entirely PDMS.

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http://dx.doi.org/10.1016/j.meddos.2013.10.006

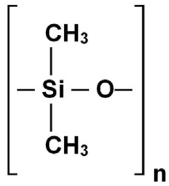

Fig. 1. Monomer unit of polydimethylsiloxane (PDMS).

For this study, 4 sample breast prostheses, 2 from each of 2 manufacturers were obtained. All 4 of these were based upon PDMS but had different sizes and surface textures as shown in Table 2. For testing water-filled devices, 3 rubber balloons were filled with tap water, distilled water, and prepackaged medical saline.

Density of materials

The primary determinant of the radiation characteristics of a material is its physical density. This value is used for calculating both the kVXCTN and pRLSP (refer to sections Kilovoltage x-ray computed tomography numbers and Proton relative linear stopping powers). In this study, the mass of each test sample was measured with Mettler PC 8000 scale (Mettler Instrument Corp., Hightstown, NJ) having a resolution of 0.1 g. To check the calibration of the scale, the mass of each sample was also measured with Digital Pediatric Tray Scale (Model 522KL, Health O Meter, Alsip, IL) with a manufacturer stated accuracy of 5 g for masses up to 9000 g. The volume of each prosthesis or balloon was determined by scanning with a kilovoltage x-ray computed tomography (kVXCT) unit, contouring the device using image analysis software and then using the image analysis tools to calculate the volume. The kVXCT scanner used was a Discovery CT950RT (General Electric Medical Systems, Milwaukee, WI). The parameters used for the scan are given in Table 1. During scanning, each device was placed on a low-density foam plate cantilevered into air beyond the end of the scanner table top to enable easy definition of the device edge during contouring. The image analysis software used for the contouring and volume calculation was Velocity Grid (Velocity, Atlanta, GA). The contouring was performed automatically using a threshold contouring tool with the threshold value set at a kVXCTN of 500, corresponding to half of the kVXCTN of the contained material.

Kilovoltage x-ray computed tomography numbers

X-ray relative linear attenuation coefficients (RLACs) of saline and PDMS to water were calculated at an interval of 1 keV between 1 and 120 keV using the program XCOM.[18] The kVXCTNs were calculated by determining the RLACs for the effective energy of the kVXCT scanner. Measured kVXCTNs were extracted from the same scans as described in the section Density of materials using a large region of interest over which the kVXCTNs were averaged.

Table 1
kVXCT scanner parameters

Parameter	Value
kVp	120
mA	250
Scan field of view diameter	250 mm (pediatric head)
Mode	Helical
Collimator width	10 mm
Effective slice width	0.625 mm
Pitch	0.562
Reconstruction type	Standard

Proton relative linear stopping powers (pRLSPs)

The pRLSPs of the test sample materials was calculated using the program LET from the Brookhaven National Laboratory.[19] Calculations with this program for several materials have previously been compared with tabulations by Janni,[20] the International Commission on Radiation Units and Measurements (ICRU) 49 report,[21] and calculations by Monte Carlo N-particle eXtended (MCNPX)[22] and were found to be within reasonable agreement.

Measurements of pRLSP were made using test samples that were sequentially placed between 2 thin plastic slabs. The distal side of the distal slab was placed at the isocenter of a horizontal proton beamline. Just distal to the slabs was placed a multi-layer ionization chamber (MLIC) (model Zebra, Ion Beam Applications, Belgium) whose layer thicknesses had been previously calibrated in terms of water by comparing measurements made with the MLIC with proton beam depth dose distributions measured in a scanning water phantom. The prosthesis samples were exposed to a proton beam with a range, as defined to the distal 90% dose level, of 160 mm of water. The energy stacking technique was combined with a miniridge filter to modulate the range to give a uniform dose distribution across 100 mm of depth. The differences in depths of the distal 90% ionization within the MLIC with and without each sample were determined and used with Eqs. (6) and (7) from the report by Moyers *et al.*[23] to determine the pRLSP and uncertainty in the pRLSP of each sample.

Results

Table 2 shows the results of the calculations and measurements. For easy comparison with physical densities and pRLSPs, kVXCTNs are presented in the table instead of the often-used Hounsfield units.

The masses measured by the 2 scales were within 0.3%; therefore, only the values from the Mettler scale with the higher resolution were used for calculating the density. The physical densities determined in this study are given in column 4 of Table 2. The 1 standard deviation uncertainty in the volume determination was estimated by assuming the shape of a prosthesis to be a hemisphere and calculating the difference in volume for a 1 pixel (0.5 mm) contouring error. The density values derived in this study are consistent with literature values within the stated uncertainties. The density of distilled water measured in this experiment was about 1.9% lower than the generally reported value of 0.998 g/cm^3 for pure water at 22°C whereas the density of tap water was only about 0.4% lower. The density of saline measured in this experiment was about 2.1% lower than the generally reported value of 1.0046 g/cm^3. Beisang *et al.*[24] reported the density of saline to be 1.00 g/cm^3 and that of silicone gel to be 0.97 g/cm^3. The average density for the silicone filling material measured in this study was 0.965 g/cm^3. Krishnan *et al.*[9] used a density of 0.98 g/cm^3 for a silicone breast prosthesis whereas Uushona[11] used densities of 0.96 and 0.98 g/cm^3 for Monte Carlo simulations of silicone breast prostheses. Allergan Medical Affairs

Table 2
Characteristics of test sample materials. Uncertainty values stated at 1 standard deviation level

Sample	Mass (g)	Volume from XCT (cm^3)	Measured density (g/cm^3)	Calculated kVXCTN*	Measured kVXCTN*	Converted pRLSP	Calculated pRLSP	Measured pRLSP
Distilled water	553.2 ± 0.4	565.00 ± 13.2	0.979 ± 0.023	1000	986 ± 4	0.994	1.000	n.p.
Tap water	950.6 ± 0.6	955.90 ± 19.0	0.994 ± 0.020	n.p.	987 ± 5	0.994	1.000	n.p.
Saline	403.4 ± 0.3	410.50 ± 10.7	0.983 ± 0.026	1010	1010 ± 3	1.010	0.998	n.p.
Sientra smooth	356.4 ± 0.3	369.68 ± 10.0	0.964 ± 0.030	1030	1123 ± 4	1.085	0.929	0.936 ± 0.016
Sientra textured	386.4 ± 0.3	399.65 ± 10.5	0.967 ± 0.025	1030	1121 ± 5	1.085	0.929	0.933 ± 0.015
Naturelle small	377.1 ± 0.3	391.52 ± 10.4	0.963 ± 0.026	1030	1120 ± 4	1.085	0.929	0.937 ± 0.026
Naturelle large	798.9 ± 0.6	826.20 ± 17.0	0.967 ± 0.020	1030	1110 ± 4	1.084	0.929	0.976 ± 0.014

* HU = XCTN − 1000; n.p. = not performed.