The Use of Directional Interstitial Sources to Reduce Skin Dose in Breast Brachytherapy

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Abstract

Purpose

To investigate the feasibility of reducing the skin dose with temporary LDR multicatheter breast implants with the use of directional ^{125}I interstitial sources in comparison to conventional HDR interstitial breast brachytherapy.

Method and Materials

The treatment plan for a patient treated with HDR interstitial brachytherapy with ^{192}Ir was compared to a directional ^{125}I treatment plan in the same dataset. Directional sources contain an internal radiation shield that greatly reduces the intensity of radiation in the shielded direction. They have a similar dose distribution to non-directional sources on the unshielded side. Several dosimetric parameters are compared including target volume coverage, dose homogeneity index, and the skin surface areas receiving 30%, 50% and 80% of the prescription dose (S30, S50 and S80, respectively). The HDR prescription dose was 34 Gy in 10 fractions.

Results

Similar excellent target coverage was achieved by both directional LDR and HDR (99.2% and 97.5%, respectively). Moreover, for a 170-cc target volume, the dose homogeneity index was 0.82 for both LDR and HDR (V100 was 211.4 cc or 225.7 cc, and V150 was 39.1 cc or 40.4 cc, respectively). However, with directional LDR, the following reductions in skin dose may be achieved: S30 is reduced from 100.6 cm^2 to 62.6 cm^2, S50 from 50.6 cm^2 to 16.1 cm^2, and S80 at 2 cm^2 to null. The reduction in V50 for the whole breast is more than 100 cm^3 (386.1 cc vs. 489.2 cc).

Conclusion

As compared to HDR, directional interstitial ^{125}I sources allow similar dose coverage to the subcutaneous target, while significantly lowering the skin dose due to a quicker fall-off beyond the target. Directional LDR sources can produce a similar dose homogeneity index, but the biological characteristics are more tolerable to the patient and can potentially reduce the risk of late skin and subcutaneous toxicity.

Introduction

Breast conservation therapy (lumpectomy) followed by patitial breast radiation therapy has been accepted as effective for early stage I and II breast tumors as mastectomy. The clinical target volume (CTV) encompasses a 1.5 cm expansion around the lumpectomy cavity, subject to modification to ensure at least 5 mm target-to-skin distance and no overlapping with the pectoralis muscle. Treating such a partial breast target has led to excellent tumor control and good to excellent cosmesis.

To ensure excellent tumor control, avoid excessive skin red spots (telangiectasia) and fat fibrosis or necrosis, strict patient selection criteria have applied to exclude tumors relatively large (> 3 cm) or superficial. "Ideal" tumors are deep tumors in large breast breasts. However, many tumors are not ideal with most tumors in the upper outer quadrant.

A high-dose-rate (HDR) out-patient receives 10, 3.4-Gy fractions over fiveconsecutive days (bid), or a low-dose-rate (LDR) in-patient receives continuous irradiation of 45 Gy to 50 Gy over three to five days. Recently, permanent breast seed implants (PBSI) using ^{103}Pd prescribed at 90 Gy have been clinically used to treat small tumors (<2 cm) deep in relatively small breasts.[1] Although the dose distribution is less homogeneous for conventional LDR brachytherapy than HDR, tumor control and late toxicities are similar.[2-5] The risk of late subcutaneous fibrosis is associated with the presence of 150% hot spots in the breast; the risk of telangiectasia significantly increases (from 1.5% to 18%) when TLD measurements on the skin indicate a dose of over 10 Gy for HDR treatments.[6] This work investigates the feasibility of reducing skin and subcutaneous toxicities further or expanding patient eligibilityin LDR treatment by using directional ^{125}I sources in interstitial catheters, implanted by a method similar to the Kuske technique.[7-8]

Methods and Materials

When organs at risk (OAR) are adjacent to tumor targets, radiaition shield is desired to protect OAR from excessive dose from brachytherapy sources. In intracavitary application, separated tungsten shield of 0.8 cm thickness has been used to shield OARs from ^{192}Ir source. The dose on the surface of shielded side is reduced to 13% of its value without the shield with slight reduction of dose on the unshielded side.[9]

However, there is limited space available for the radiation shield to achieve the desired directional dosimetric distribution within interstitial brachytherapy sources of 0.8 mm diameter crossstection. Low energy gamma-emitting isotope can be shielded with very thin high-Z materials. The tenth value layer (TVL) of lead is 0.025 mm for ^{103}Pd, 0.08 mm for ^{125}I comparing to 8 mm for ^{192}Ir. Therefore, it is possible to integrate an internal radiation shield within interstitial brachytherapy sources to shield one side's dose at 1 cm below 10% that of the other side. When the radiation shield is thicker than twice of TVL, the shielded side's dose primarily come from scatter with minimal contribution from primary radiation (below 1%).

The design of directional interstitial brachytherapy sources have been optimized per the internal shielding material, the isotope carrying substrate, the shapes of isotope carrier and shields, the relative position and size between the carrier and the shield. The goal is to achieve angularly uniform 180 degree sector, sufficiently shielded 90 degree sector with a sharp gradient between the treated and shielded regions in the transverse plane of the source. The optimized design will henthforth be referred as uniformly treated half and sufficiently shielded quarter and can be accomplished with a simple design as in Fig.1.

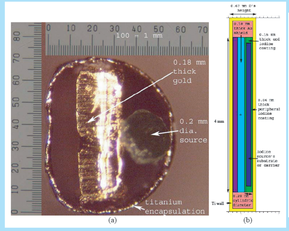

Figure 1: (a) Microscopic transverse plane cross section across the source axis (b) MCNP4 generated cross section across the gold shield and along the source axis of the first directional source

In Fig. 1, a low-Z nylon filament (0.2 mm diameter) labeled with ^{125}I is placed on the top of a 0.6 mm wide and 0.2 mm thick gold shield. The filament and the gold shieldare 4 mm long. As in Fig. 1b, the surface of the nylon filament is coated with ^{125}I , preferably on both ends. The source components are contained in a D-shaped titanium tube that was reshaped from a pair of 0.8 mm outer diameter and 5 mm long cylindrical tubes.

In Fig. 2, the dose distribution from the first directional source is simulated with Monte Carlo transportation code MCNP4C3 and updated cross section library mcnplib4. Because of the low energies involved, electrons were not transported. Track length estimator of the collision kerma f6 tally is used to approximate dose. The uniformly treated half, shielded quarter and sharp gradient zones are shown in the dose distribution on the transverse plane in Fig. 2a. This source has a nearly isotropic dose distribution over the half sphere of the treated side; small peaks can be found at the top and bottom in Fig. 2b. These dosimetric characteristics are due to the low-Z isotope carrier and uniform titanium container thickness at the source ends. Note that conventional sources are isotropic in the radial direction and have small dips instead of peaks on the tip and bottom of the source's longitudinal axis. High-Z materials are laid parallel to the isotope carrier in directional sources but along the source axis in conventional sources. Low-Z isotope carrier and parallel layout of high-Z shield explain the small peaks instead of dips at the top and bottom of dose distribution and more isotropic characteristics from directional sources.

Isodose surface is plotted for a permanently implanted source in Fig. 2b. However, the same dose kernel simulated at 0.1 cm resolution for a 12 by 12 by 12 cm^3 cube can be scaled for temporarily implanted sources per Equation 1:

$$S=S_p*RT_{1/2}/(D_p*\ln 2) \quad (1)$$

For the temporary LDR breast implants, treatment plans can be optimized as permanent implants first. S_p and D_p are optimized source strength and prescription dose for a permanent plan respectively. At dose rate R, optimized S_p can be converted to optimized strength S For a temporary implant. $T_{1/2}$ is the decay half-time of the isotope ^{125}I, i.e. 59.4 day. The same source strength as conventional sources has been assigned to the directional sources so that conventional sources can be replaced with directional sources with negligible dose change to the unshielded side. Source strengths of about 3-5 U are used for breast temporary treatments of 50 Gy in 120 hours or 0.42 Gy/hour, compared with an initial dose rate of 0.15 Gy/hour for permanent ^{103}Pd breast implants of 90 Gy.

To ensure a fair comparison between LDR and HDR implants regarding side effects, biologically effective dose (BED) is used as well as physical dose for the normal tissue with α/β at 3 Gy and repair half-time at 1.5 hour. Comparable side effects exist for LDR and HDR implants per Equation 2:

$$R=1/2*(\alpha/\beta)/(G*T)*[(1+4*G*BED/(\alpha/\beta))^{1/2}-1] \quad (2)$$

where G is the protraction factor associated with relatively long treatment duration compared to HDR, G is approximately 1 for HDR but much smaller for LDR treatments.

The HDR treatment plan In Fig. 3a uses ^{192}Ir compared with the LDR plan In Fig. 3b that uses ^{125}I, where some conventional sources have been replaced with directional sources. Only template positions confined by the Kuske template are considered for the placement of directional sources to ensure the same physical constraint. Both catheter and plane spacing are set at 1 cm instead of 1.5 cm to account for the shorter penetration of ^{125}I as compared to ^{192}Ir. Fig. 3 shows a CT slice of a right breast, with the target outlined by a thick red line in Fig. 3a and a white line in Fig. 3b, and the seroma outlined in light blue in Fig. 3a. The figure also shows solid isodose lines in HDR and correspondingly in LDR, respectively. For this patient, a total of 25 slices are outlined with ROI contours encompassing 22.2 cc of seroma and 170.9 cc of target. In Fig.2b, seven out of 14 conventional sources are replaced with directional ones.

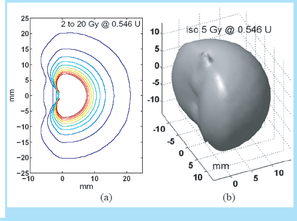

Figure 2: (a) Dose contours on the transverse plane across the source axis (b) Isodose surface at 5 Gy from the dosposition of the first directional source permanently implanted with the strength of 0.546 U

The directional sources can be used for one of three purposes: (1) to reduce skin dose (D10), (2) to improve dose uniformity within the subcutaneous tumor target (E9, F8, A5 and A4) and (3) to reduce the volume of dose in the fat outside the target (D2 and A9). The three uses of directional sources can be applied independently by orienting the shielded side of a directional source towards the skin, an adjacent source, the outside of the tumor target, respectively. All three uses have been applied in Fig. 3b to show the possible improvement that can be achieved for this patient.

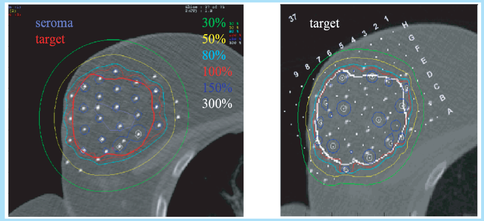

Figure 3: Isodose and ROI plots in HDR left (a) & directional LDR right (b) on a CT image with target (thick red line in (a) and white line in (b)) and seroma (light blue in (a) only) contours. Directional source orientations may be inferred from the 150% isodose line at the grid positions. For example, the source is shielded toward the skin at D10 but subcutaneous tissues at E9 & F8.

Results and Discussion

Thirty one catheters are used in both cases. The LDR treatment uses 61 directional sources plus 96 conventional sources, and the HDR treatment requires 8 minutes of irradiation with a 6 Ci 192Ir source. Orientations of directional sources are manually determined to make the prescribed dose distribution conformal to the target, cover skin minimally by the 30% and 50% isodose lines, and minimize 150% hot spots within the breast. For normal tissues, the isodose lines at 30%, 50%, 80%, 100%, 150% and 200% of 3.4 Gy in 10 fractions in HDR are biologically equivalent to the isodose lines at 26%, 46%, 78%, 100%, 157% and 217% of LDR dose at 45 Gy in 108 hour , respectively, for late complications.

Fig. 4 shows the dose-volume histogram (DVH) for the treated target in HDR (a) and directional LDR (b). The tumor target coverage is similarly excellent for conventional HDR and directional LDR implants (97.5% vs. 99.2%). Doses from 100% to 300% of the prescribed doses are similar up to 200% for both implants as well. The tail of the DVH curve is slightly higher in LDR than HDR beyond 200%, these hot spots are from the center of dose kernels. ^{125}I has an energy lower than ^{192}Ir. the center of dose kernels are relatively bigger as dose decays quicker from the center. Since all these hot spots are from discrete brachytherapy sources, they are well tolerated as long as they remain separate.

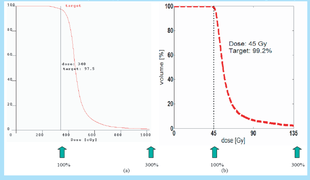

Figure 4: Dose volume histograms for the tumor target of (a) conventional HDR implant (b) directional LDR implant (relative 100% and 300% doses shown at 340 cGy and 1020 cGy for HDR and 45 Gy and 135 Gy for LDR implants)

In Table 1, Vx is the absolute volume of the ipsilateral breast receiving at least x percent of the prescribed dose and Sx is the absolute skin surface area receiving at least x percent of the prescribed dose. For each column in Table 4.4, the heading labeled x/y indicates the S or V values for the x% isodose line in HDR or LDR implant (1st or 2nd row), and for the y% isodose line in LDR impalnt (3rd row), where the y% isodose line in LDR is biologically equivalent to the x% isodose line in HDR with respect to late complications.

Table 1: Volume of dose in the fat and skin dose for both directional LDR plan of 45 Gy in 108 hour and conventional HDR plan in 10 fractions of 3.4 Gy that have the same relative physical or biological dose

	S30/S26	S50/S46	S80/S78	V50/V46	V100/V100	V150/V158	DHI
HDR	100.6 cm^2	50.6 cm^2	2 cm^2	489.2 cc	225.7 cc	40.4 cc	0.82
LDR	49.5 cm^2	8.5 cm^2	0 cm^2	362.8 cc	214.4 cc	39.1 cc	0.82
LDR$_{flat}$	62.5 cm^2	16.1 cm^2	0 cm^2	386.1 cc	214.4 cc	34.2 cc	0.85

Table 1 shows a 50% reduction of S30 when a directional LDR implant is used instead of the conventional HDR implant, and S30 for HDR implant is 38% higher than the biologically equivalent S26 in LDR implant. S50 is reduced from 50.6 cm2 to 16.1 cm2 in the LDR than the HDR implant. No S80 is present in the LDR implant, but there are two small separate areas in the HDR implant totaling 2 cm2. Sparing of the fat of the ipsilateral breast is also improved by using directional 125I LDR instead of 192Ir HDR implant, with more than 100 cc reduction of V50. V150 are similar for both LDR and HDR implants, meeting Wazer's criteria of V150 less than 45 cc. However, these hot spots are expected to be better tolerated when the LDR implant is used, since V158 is 34.2 cc instead of 40.1 cc for the V150 in the HDR implant. The dose homogeneity index (DHI) is similar for both implants since both V150 and V100 are similar and DHI is defined as 1-V150/V100.

Conclusion

In summary, the skin toxicity is potentially reduced in directional LDR than conventional HDR due to the more rapid dose fall-off beyond the target. The toxicity is potentially reduced in the directional LDR compared to the conventional HDR implant due to better radiobiologic tolerance of hot spots in the LDR implant although similar volume of hot spots are present in both implants.

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