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Beam characteristics and leakage assessment of an in-house intra-operative electron applicator system

P. Shokrani* **and M. Soltani**

Isfahan University of Medical sciences, Department of Medical Physics, Isfahan, Iran

▶ ***Original article***

***Corresponding author:**
Dr. Parvaneh shokrani,
***Fax:** +98 311 6688597*
***E-mail:** Shokrani@med.mui.ac.ir*

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ABSTRACT

Background: Intraoperative radiation therapy (IORT) technique is used to treat a surgically exposed tumor or tumor bed in the treatment of locally advanced intraabdominal, retroperitoneal, pelvic, thoracic, breast and soft tissue tumors. One way to perform IORT is to use an existing linac and modify the treatment head using an applicator system. In this study the objectives were to design, and build an in-house IORT applicator system, perform an acquisition of dosimetry data and characterize the IORT radiation parameters. ***Materials and Methods:*** IORT applicator system developed in this research consists of three flat applicators with inner diameters (ϕ) of 3, 5 and 9 cm and one tube (ϕ =3 cm) with a 45-degree beveled end. Beam characteristics evaluated include percent depth dose distributions, beam profiles, and leakage dose distributions. Measurements were performed using a Scanditronix (p-si) diode field detector in a Scanditronix (RFAplus) 3-D water phantom. ***Results:*** Compared to the standard applicator, depth dose curves for intra-operative cones are shallower; surface dose is higher and the maximum peripheral dose is in the order of 9.6%. ***Conclusion:*** Using a 10 MeV electron beam, the cone system developed in this study is suitable for treating tumors of width and depth ranges of 1.9-8.4 cm and 14-29 mm, respectively.

Keywords: *Intra-cavitary cone, IORT, electron boost.*

INTRODUCTION

Intraoperative radiation therapy (IORT) is a technique in which surgery and radiation therapy is combined to treat a surgically exposed tumor or tumor bed. In this technique a single radiation dose on the order of 10 to 20 Gy is used in order to improve local control while normal tissue toxicity is decreased by either shielding or displacing adjacent radiosensitive normal tissues. IORT is also used in combination with chemotherapy or as a boost to external photon beam therapy (1-4). There are several indications for this treatment: shrinking the tumor in order to simplify subsequent surgical resection, treatment of unresectable gross tumors and treatment of microscopic cells left behind in tumor bed after a complete resection. An IORT team includes the radiation therapy members as well as the members of surgical and anesthesia teams. The CTV is defined by the surgeon and radiation oncologist during the surgery (4-7). IORT technique is used in the treatment of locally advanced intraabdominal, retroperitoneal, pelvic, thoracic, breast and soft tissue tumors (2-3,8-9). However, the largest experience with IORT and the best evidence for its potentials exists in breast cancer where a substantial number of patients have already been treated. IORT requires an operating room and a medical linear accelerator (linac). Although using a mobile electron linac is more desired, the simplest way is to use an existing linac and just modify the head of the machine by design and fabricating of an applicator system (2, 10-17). In this study the objectives were to design, and build an in-house IORT applicator system, perform an acquisition of dosimetry data and characterize the IORT radiation parameters.

MATERIALS AND METHODS

An IORT applicator system was made for a Neptun 10PC linear accelerator (manufactured in Poland by IPJ-ZdAJ Świerk). A complete description of the treatment head and linac specifications have been reported elsewhere (18). This machine has nominal electron energies of 6, 8, and 10 MeV. Electron field size and electron mode activation is performed using a set of applicators (standard applicator). The standard applicator is connected to the X-ray jaws. Therefore, X-ray jaw setting changes when electron field size is changed.

The IORT applicator system is consisted of the following parts: 1) main tube, 2) adaptor tube, and 3) a connector ring (figure 1). The main tube is the tube that will be in contact with patient. Four acrylic tubes with inner diameters (ϕ) of 3, 5 and 9 cm and one tube (ϕ =3 cm) with a 45-degree beveled end which is suitable for uneven surfaces were selected to cover most tumor sizes. The adaptor tube is placed on top of the acrylic tubes in order to minimize radiation leakage to outside of the treatment area. Two adaptor tubes were used: a brass tube of 1 mm wall thickness for 3 and 5 cm acrylic tubes and an aluminum tube of 5 mm wall thickness for the 9 cm tube. The acrylic tubes slide up and down inside the adaptor brass tube for setting up the patient conveniently. The connector ring is a plastic ring that is fixed on top of each adaptor tubes and connects the adaptor tube to a 3 cm thick aluminum plate, via a circular opening machined in the center of the plate. The aluminum plate was used to attach adaptor tube to the treatment head and to minimize the leakage to the patient. In order to adopt the applicator system to other makes of linacs, only the aluminum plate should be modified.

To fix the applicator system to the treatment head, one of the machine's wedge holders was used as a holder for the aluminum plate. The electron mode activation mechanism was not modified. In order to activate the electron mode, the top part of standard electron applicators that include the electron mode micro switches were separated and were attached to the X-ray jaws. When the wedge holder and the micro switch assembly are connected to the treatment head, the minimum possible electron field size is 5×5 cm^2 (corresponding to X-ray jaws setting of 15×15 cm^2).

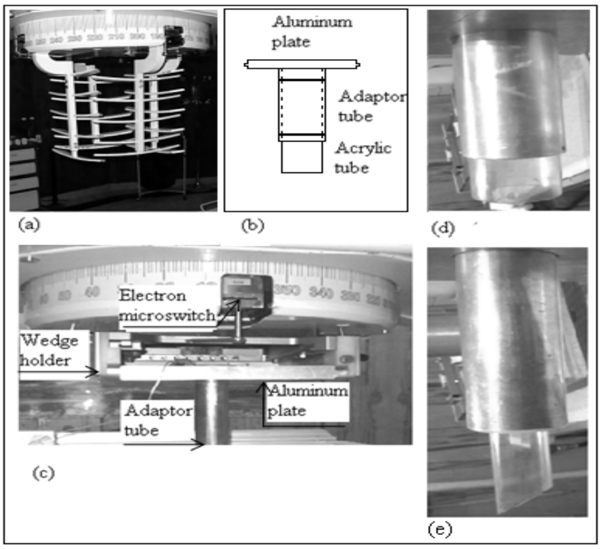

Figure 1. The applicator systems: (a) the standard applicator, (b) the IORT applicator system diagram, (c) an adaptor tube connected to the treatment head via an aluminum plate and a wedge holder, also showing one of 4 electron micro switches used to activate the electron mode, (d) a flat end applicator connected to the Aluminum plate and (e) an applicator with oblique end.

Dosimetry

All measurements were done using a 10 MeV electron beam. Measurements were performed in water using (p-si) diode field detectors in a 3-D automatic water phantom (RFAplus), both made by Scanditronix in Sweden.

When the flat tubes are correctly docked in the aluminum plate, the end of the tube is placed on the water surface at 100 cm (SSD). For these tubes, PDD data were measured along the beam central axis. For the beveled-end tube, the gantry was rotated until the end of the cone was flush with the water surface. In this gantry position, the PDD curves for the beveled-end cone were measured at the center of the field and perpendicular to the water surface.

For all tubes, tube ratios were obtained at the depth of maximum dose and relative to the output of a 10×10 cm^2 field made by the standard electron applicator. To find the optimum jaw setting that gives the highest cone ratios and appropriate profiles, the measurements were done for X-ray jaw settings of 15×15 and 20×20 cm^2. All measurements were repeated for a 5 cm gap. The gap is the distance between end of the tube and water surface.

For leakage measurements, the end of each tube was covered with a plastic sheet to prevent water from entering into the cone. Subsequently, tubes were inserted into the water up to 10 cm of their length. The measurements were performed in two directions: perpendicular to the tube, at depths of 18, 28 and 37 mm and also along the tube's length, 20 mm away from the tube's wall.

RESULTS

Figure 2 shows depth dose distributions for standard electron applicator (field size 5×5 cm^2) and intra-cavitary cones, all measured in X-ray jaw setting of 20×20 cm^2 at 100 cm SSD. Depth dose curves for intra-operative cones tend to be closer to the surface. Values for surface dose (D_0), depth of maximum dose (dmax) and therapeutic range (R_{90}) of standard electron applicator (field size 5×5 cm^2) and intra-cavitary cones are listed in table 1. All Values were measured for two X-ray jaw settings of 20×20 and 15×15 cm^2 and at two distances of 100 and 105 cm SSD. These values provide information for prescribing field characteristics and dose calculations. Relative to the d_{max} and R_{90} for standard applicator, the similar depths are about 4 mm shallower for 5 and 9 cm cones, about 6 mm shallower for 3 cm flat-end applicator and 9 -12 mm shallower the 3 cm beveled-end applicator.

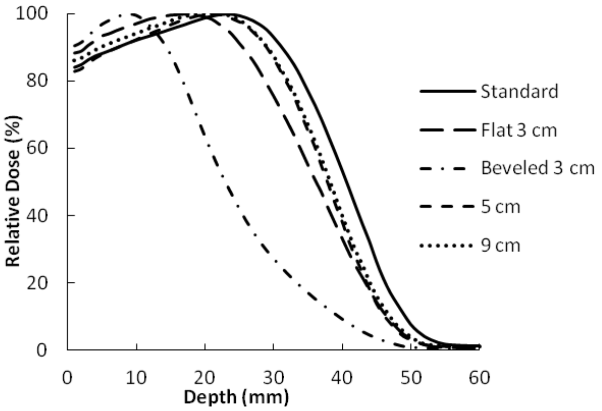

Figure 2. PDD curves for flat and beveled (3 cm), 5 and 9 cm applicators and standard applicator (5×5 cm2 field size) in X-ray jaw setting of 20×20 cm2 and at SSD=100 cm.

In (IORT) it is important to assure an adequate surface dose. Compared to the standard applicator, measured surface dose values are higher for intra-cavitary cones and increase with X-ray jaw settings and obliquity of beam incidence (table 1). Data measured for 3 cm applicators at different SSDs show that the effect of the 5 cm gap on depth dose distribution is not significant (0.1 -1.9% change in surface dose and 2-3 mm change in both R_{50} and Rp). The data also show that for both flat and beveled applicators, the depth dose distribution are independent of X-ray jaw setting.

In table 2, depth of 50% dose (R_{50}) and electron practical range (R_p), the information necessary for dosimetry and shielding, are provided. For 5 and 9 cm applicators, R_{50} is reduced about 4 mm relative to the R_{50} for standard applicator. For 3cm flat-end and beveled-end applicators, R_{50} are 4 and 18 mm shallower respectively, compared to R_{50} for standard applicator. R_p is shallower about 4 mm for 5 and 9 cm applicators and 3 and 16 mm for 3 cm flat and beveled end applicators relative to R_p for standard applicator.

Figure 3 shows beam profiles for 5 and 9 cm applicators measured at depths 10 mm, d_{max} and R_{90} at SSD=100 for X-ray jaws of 20×20 cm^2. These profiles are used to select the applicator size for optimum lateral coverage of tumor. Lateral profiles show high dose regions (horns) inside the edge of the applicator wall (a shallow profile for 5cm and all profiles for 9cm applicators). A max of 10% horn is seen at d_{max} for 9 cm applicator These high dose areas are due to scattering electrons through the collimation system and the acrylic wall.

When treaing a tumor volume with an irregular contour, an air gap may occur between the applicator end and the treatment surface. The effect of air gap (or change in SSD) on beam profiles at dmax was studied for the smallest applicators as shown in figure 4. A 5 cm gap does not show an effect on beam penumbra or size for either of the flat or beveled 3 cm applicators. However, the profile is displaced with respect to the central axis for the flat applicator, in contrast to the beveled one.

The radiation leakage dose distribution along the length of applicators and 20 mm away from their wall as a percentage of doses at d_{max} is illustrated in figure 5. It is shown that radiation leakage is larger for smaller applicators. The characteristic shape of the curves; a build up region, sharp fall out and a tail with constant dose, shows that the radiation leakage outside of the applicators are due to both X-rays and electrons. The quality of the leakage electrons outside of the wall of the applicators, calculated using E_0=2.33 R_{50} (MeV), is about 3-5 MeV and its maximum value is about 10% of the dose at d_{max}. It is also seen that electron leakage is limited to the depth of 3 cm, when the applicators are inserted 10 cm deep in water. At larger depths, the leakage dose is only due to X-rays, which is about 1% of the dose at d_{max}. The max radiation leakage for the smallest cone measured perpendicular to the applicator wall, was 30% for X-ray jaw setting of 15×15 and 9.8% for jaw setting of 20×20 cm2, relative to the dose at d_{max}.

Table 1. Surface dose (D_0), as a percentage of maximum dose, depth of maximum dose (d_{max}) and depth of 80% dose ($d_{80\%}$) for standard and intra-operative applicators, for different X-ray jaw settings and SSDs.

	X-ray jaw setting (cm^2)	SSD = 100 cm					SSD = 105 cm	
		Applicator						
		Standard*	3 cm (Flat)	3 cm (Bevel)	5 cm (Flat)	9 cm (Flat)	3 cm (Flat)	3 cm (Bevel)
D_0 (%)	15×15	84.2	86	90.9	_	_	87.4	92.7
	20×20	82.2	87.9	91.8	82.9	86.1	88	92.9
d_{max} (mm)	15×15	23	18	9	_	_	17	8
	20×20	25	19	10	21	21	19	9
$d_{80\%}$ (mm)	15×15	34	29	16.8	_	_	29.5	16.6
	20×20	34.2	29.5	16.8	32	32	30	16.5

* Electron field size of 5×5 cm^2

Table 2. Depth of 50% dose (d_{50}) and practical range (R_p) (mm) for standard and intra-operative applicators measured with different X-ray jaw settings and SSDs.

	X-ray jaw setting (cm^2)	SSD = 100 cm					SSD = 105 cm	
		Applicator						
		Standard*	3 cm (Flat)	3 cm (Bevel)	5 cm (Flat)	9 cm (Flat)	3 cm (Flat)	3 cm (Bevel)
d_{50} (mm)	15×15	41.5	36.3	23	_	_	37.2	23.9
	20×20	41.5	36.2	22.6	38	38	37.3	23.7
R_p (mm)	15×15	40.5	46.7	35.1	_	_	46.5	37.1
	20×20	50.9	48.1	35.2	46.8	47.1	48.8	37.6

*Electron field size of 5×5 cm

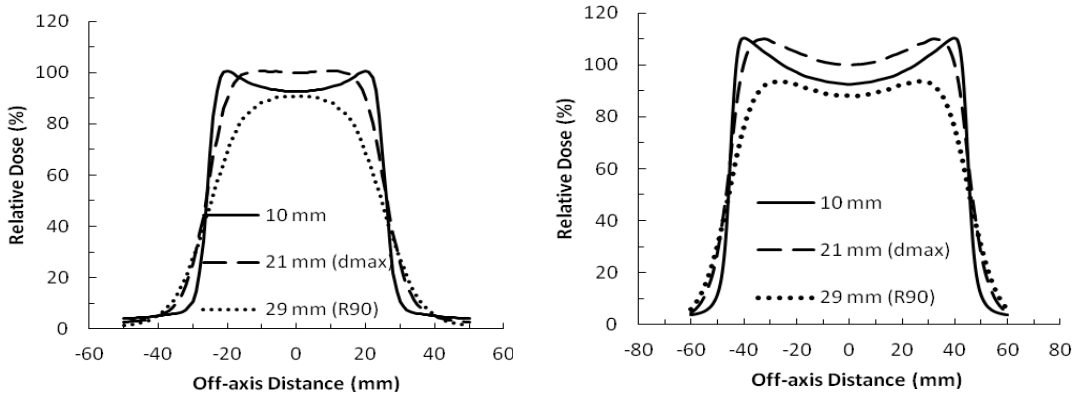

Figure 3. Beam profiles measured for 5 cm applicator (left) and 9 cm applicator (right) at depths 10 mm, dmax and R90 at SSD=100 for X-ray jaws of 20×20 cm2.

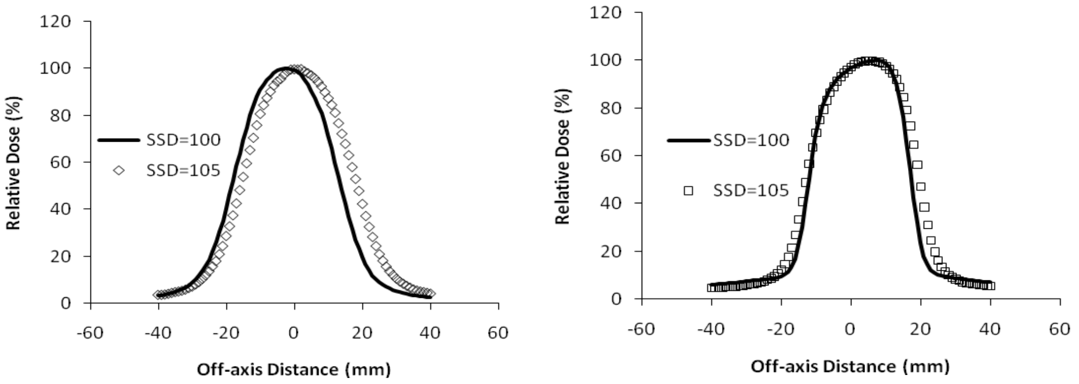

Figure 4. Beam profiles measured at dmax at SSD=100 and 105 cm for 3 cm flat (left) and beveled cones (right).

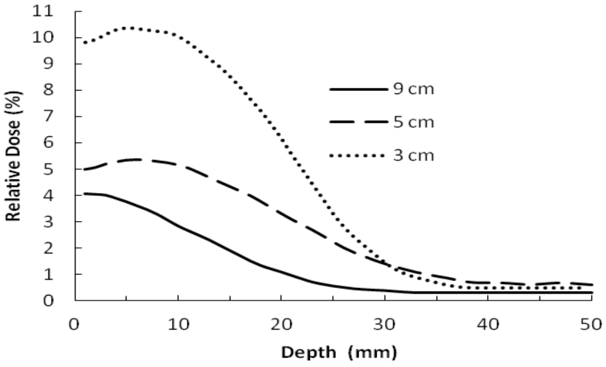

Figure 5. The radiation leakage curves along the length of applicators with X-ray jaw setting of 20×20 cm^2.

DISCUSSION

In this research an electron beam intracavitary cone system was developed for delivering high doses to tumor or tumor bed during surgery. This system, adapted to a Neptun 10 PC linear accelerator, can be adapted for different makes of linear accelerator. The dose distribution in this new design system shows an acceptable dose homogeneity and small leakage radiation dose to tissues outside the intraoperative cone. Using a 10 MeV electron beam, the applicator system can be applied to treat planning target volumes (PTV) at depth ranges of 14-29 mm. Considering the width of 90% profiles at dmax, these cones are suitable for lateral coverage of tumors in range of 1.9-8.4 cm width. Axial and lateral coverage may be extended if a lower isodose line like 85% or 80% is chosen to cover PTV.

Relative to the standard electron applicator, PDD curves for oral cones tend to be closer to the surface and beveled end applicator has the shallowest PDD. The shift of PDD curves towards the surface occurs as a result of scattering of electrons through the applicator system and the acrylic wall which tend to increase the mean scattering angle of the electrons. Surface dose as a percentage of doses at d_{max} for each cone ranged from 86% to 92.9%, a maximum of 9.6% increase compared to the surface dose for the standard applicator (for X-ray jaws of 20×20 cm^2). Bjork et al reported a maximum of 2% increase in surface dose using the IORT cones and used a 0.3-cm slab of PMMA positioned at the level of the tertiary collimator to increase the mean scattering angle of the electrons and thereby to increase the surface dose (9).

A max of 10% horn is seen at d_{max} for the largest applicator. These high dose areas are due to scattering electrons through the collimation system and the acrylic wall. One approach some investigators implemented to reduce the horns is to decrease the number of electrons striking the cone wall: inserting a ring of brass, steel, or plastic inside the cone to decrease the electron fluence striking the lower portion of the cone (2, 13). They have reported that an intermediate ring reduces the hot spots, but sacrifices the coverage of the therapeutic range.

In IORT, radiation leakage is an important issue, since a large single dose of radiation is delivered, and normal tissue surround considerable parts of the cone wall. The radiation leakage through the cone is defined as the absorbed dose 2 cm outside the inner diameter of the cone. In this research the maximum radiation leakage through the cone was about 9.8% of the dose at dmax, compared to clinically acceptable value of below 13% (9). This value was measured for the smallest cone and largest jaw setting. The radiation leakage close to the water surface originates primarily due to bremsstrahlung photons originated in the photon jaws, or scattered electrons in the air. Leakage was reduced by using a 3cm aluminum plate as tertiary collimator, to attach the adaptor tube to the treatment head. Leakage was further reduced from 30% to 9.8% by selecting the largest photon collimator setting, i.e. 20×20 cm^2. The increase in absorbed dose along the cone wall is a result of leakage through the wall itself. A number of researchers have used metallic cones, but at the expense of decreased visibility (7). In this research adaptor tubes of proper material and wall thicknesses were used on top of the acrylic tubes to reduce the leakage radiation along the wall.

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