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Research Article

Shielding Effects on Low-KVIORT Forward Projecting Applicators

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Abstract

Motivation/Purpose/Scope: The low-KV x-ray Intra-Operative Radiotherapy (IORT) Spherical Applicators (SpA) system enabled post-breast-lumpectomy IORT [1,2]. Zeiss Meditec AG recently introduced two low-KVIORT Forward Projecting Applicators (IFPA); they are the low-KVIORT Flat Applicator (IFA) and the low-KVIORT Surface Applicator (ISA) for post-surgical-tumorectomy radiation treatment in the pelvis and abdomen. It has also successfully used for skin cancer treatment. The dosimetric characteristics of these applicators were studied and reported [3,4].

Clinical presentation of lesions in skin cancers [5], is usually in irregular patterns. For maximum protection of normal tissues in conforming the circular shaped fields to the shape of the lesion, it is necessary to shield or shape the circular applicator accordingly using lead sheet. Adding custom shielding or collimation to shape the circular field would affect the Dose Rate (DR), Percentage Depth Dose (PDD) and the Divergence (DV) of the calibrated open cone. The purpose of this study is to understand the dosimetric relationship between size and shape of the shielding on the DR, PDD and DV from the open cones. We conducted an investigation to evaluate if the long established "Equivalent Square" formulation [6] is a reasonable estimate for DR and PDD for the different cones and irregular shape shielded fields.

Results: We investigated the DR, PDD, and divergence using six different elongated shapes carved in commercially available lead-foil for the largest applicators of each of the IFA and ISA. The DR differences between various sizes of shielding to the open cone varies widely as a function of shielding sizes, shapes, type, size of the applicators and the depth of interest. At five mm depth, dose rates vary from 6% higher to 14% Lower than the open cone for the 6-cm IFA. The 4-cm cones DR vary from 5% to 25% Lower than the open 4-cm IFA, and from 2% to 20% lower than the open 4-cm ISA.

The general trend on the effect of the shielding for the PDD shows a decrease of 1% at shallow depth and up to24% at greater depths. The greatest changes are with the large cone, shielded with small cutout at 3 cm depth. However, there is an increase of PDD up to 10% for the 4-cm cone shielded with a small cutout at the first few millimeters depth.

The degree of divergence is dependent on the Target to Surface Distance (TSD) of the cones. The 6 cm IFA cone has larger TSD than the 4 cm cones. The 4cm ISA& 4cm IFA has identical TSD; and has similar divergence for the same shielding aperture; the 6cm IFA has slightly smaller divergence than those with 4cm ISA& 4cm IFA with the same shielding aperture.

Conclusions: Preliminary analysis indicates the Equivalent Square formulation fails to apply in the IFPA because off our fundamental differences: the IFPA cones has dissimilar TSD, variable filtration, beam quality variance with field size and scattering contribution from cut-out, and dose rate changes with field size. All these factors contribute to the difficulty applying equivalent square formulation in determination of DR, and PDD between the different size cones.

Currently, there is no established equivalent square table or rule of thumb formula for the IFPA cones.

Keywords: *Shielding; Low-KVIORT; Percentage Depth Dose (PDD); Target to Surface Distance (TSD); Intraoperative Radiation Therapy (IORT)*

Introduction

The Low-KVx-Fay IORT system is a novel design for intraoperative applications. The properties of the X-ray of the Low-KVIORT X-Ray Source-4 (XRS) have been thoroughly investigated [8-14]. Different applicators are adapted to the XRS for specific clinical applications. The design of IFA and ISA applicators makes them well suited for gastrointestinal Intraoperative Radiation Therapy (IORT) and skin tumor External Beam Radiation Therapy (EBRT).

The Low-KVIORT x-ray source is a 50 kV 40 mA miniature linear accelerator (figure 1a) [15]. Electrons produced at the cathode gun are accelerated to the desired energy (50 kV), and, with the help of steering coils, directed down an evacuated field-free tube to a thin-film gold target on the inside of the x-ray window, producing an isotropic x-ray distribution from the tip of the 3 mm diameter drift tube. The position of the virtual target is at 160 mm from the base (Figure 1b).

Different sizes of the IFPA applicators are available with different Target-Surface-Distance (TSD). Larger sizes require larger TSD. Flattening filters at the end of the cones are necessary to modify the spherical isodose distribution to give flat dose distribution for each individual applicator. The IFA applicator filters yield laterally uniform isodose line at 5 mm from the applicator surface. The ISA filter gives a uniform isodose line at the surface. This author and others [3,4] reported these data.

Adding shape shielding of different size and shape perturbs the radiationfluence of the original cone and modifies the beam characteristics of the resultant or transmitted radiation beam.

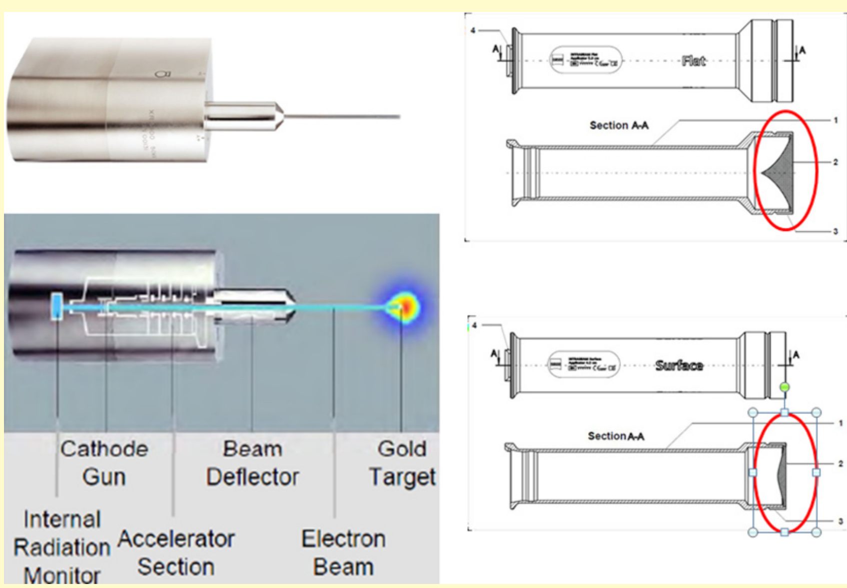


Figure 1a: *Low-KVIORT X-Ray Source-4 (XRS) and IFPA applicators: top left: XRS; bottom left: cut-away view of XRS components; top-right Flat (IFA) applicator; bottom right Surface (ISA) applicator. Note the difference of the flatness filters for the IFA and ISA (marked by red ellipse).*

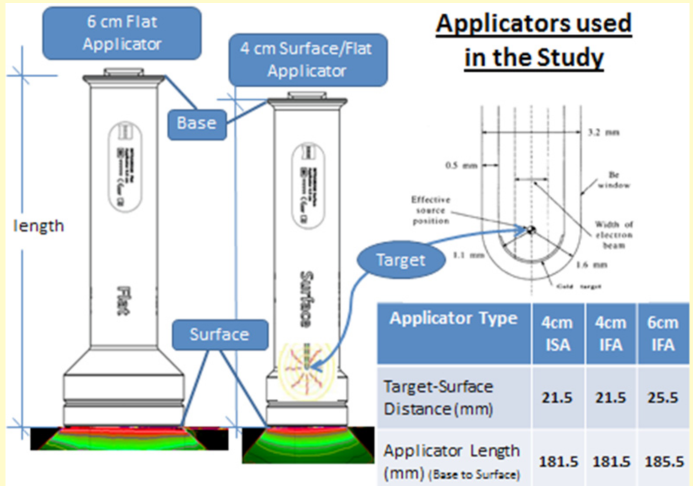


Figure 1b: *Low-KVIORT IFPA applicators: far-left: 6 cm Flat (IFA) applicator,middle 4 cm surface (ISA) applicator (4 cm IFA has same dimension except the flattening filters at the end of the cones is different). Top-right: a magnified XRS target tip diagram showing the virtual position of the target; bottom right tabulated data of Target-Surface Distance and total applicator length of the three applicators used for this study.*

This manuscript reports on the findings discovered for these IFPA applicators, on how the and the effects of added shielding on the resultant DR, PDD and divergence. We also investigate the validity of using the "equivalent square "formulation for the low-KV IORT system.

Materials and Methods

Lead alloy sheet

The alloy contains elements of TIN/LEAD/SILVER/CADMIUM/ANTIMONY/BISMUTH (Thickness: 0.1524 mm, Density: 7.2 - 11.63 gm/cc per manufacturer specification [7].) We used the Digital scale (Denver Instrument, Model PI - 403N) to measure the density of the batch of lead-foil we use. It is10.19 ± 0.01 gm./cc as compared to published data of pure lead of 11.34 gm./cc density.

The IFA applicator series has six cone sizes ranging from 1 cm diameter to 6 cm diameter in 1 cm increments. The ISA cone series has four sizes ranging from 1 cm diameter to 4 cm diameter in 1 cm increments. The flatness filters are custom designed for each applicator. The filter is part of the close-end plate of the cone. Each applicator possesses a custom flattening filter that is part of the closed end of the cone.

Generally, one can model irregular shape and size with rectangular shape field. For this investigation, we used the largest cones of each group. The largest cone size for the IFA and ISA is 6 cm and 4 cm diameter, respectively. The 4-cm IFA was also investigated in order to compare with the 4-cm ISA.

The large group has the long axis larger than 4 cm, while the small group has the long axis smaller than 4 cm (Figures 1c). This study uses the small group shielding foil with the 4 cm cones on both IFA and ISA. This study uses the large group plus the small group shielding foils with the 6-cm IFA.

EBT Gafchromic™ film (Ashland Specialty Products EBT2 Gafchromic™ Film) was deemed appropriate [16-19]. For this study, we use the film tightly sandwiched in a solid water phantom for radiation distribution measurement. We used the Radia V1.8.manufactured by Radiological Imaging Technology (RIT) of Colorado Spring, U.S.A. to analyze the films.

Figure 1c: *Cut-outs of two different groups: large and small rectangular cut-outs utilized to shape the treatment field.*

	6-cm Flat	4-cm Flat	4-cm Surface
Large Group	x		
Small Group	x	x	x

Table 1: *study comparisons with different applicators. 6 cm IFA: comparing effects of the large and small shielding groups; small group: comparing effects of different applicators.*

DR and Lead Transmission measurement

A Soft X-Ray Parallel Plate Chamber 0.0053 cm^3(PTW TN23342)was used for both in-water and in-air measurements inside the high precision Low-KVIORT Water Phantom. See Figure 2b. The mechanical positioning accuracy of the phantom stage stand is ± 0.1 mm.

The output stability of the XRS is monitored by a system of internal radiation detectors for feedback control of the beam current and position steering [20]: The Internal Radiation Monitor (IRM) inside the XRS monitors and corrects the beam intensity and beam steering to conform to specifications at 105000Hz. A Photodiode Array (PDA) of five photodiodes at orthogonal positions is maintaining isotropy, and the Probe adjuster/ionization chamber holder (PAICH) is to ensure the straight path of the electron drift tube (Figure 2a). There is a set of pre-treatment quality assurance for each treatment.

The Unidose E T10010 electrometer was used in current mode (Pico-Amperes).

Mounted on an adjustable stage, the XRS was secured to the water phantom source-stand. A fixed distance of the chamber to the surface of the applicator was maintained for different cone lengths. For all applicators, a 1-mm air gap was maintained between the applicator and the shield platform for insertion of different shielding foils. The outside circumference for each applicator size is marked on the foil for reproducible placement for centering the cut-out area (Figure 2a).

PDD measurement

For depth dose measurements, we used the Zeiss water-phantom with water level adjusted to just touching the surface of the applicator.

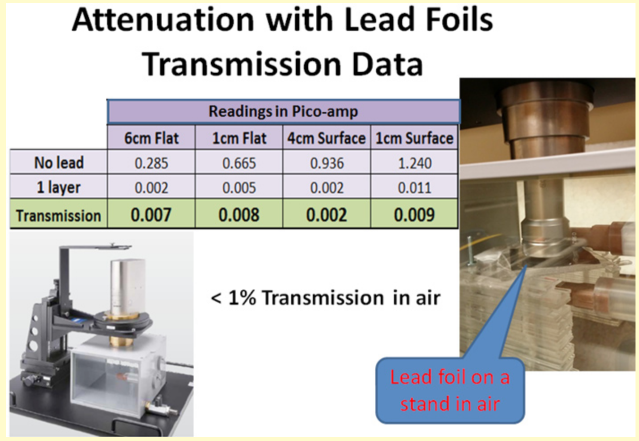


Figure 2a: *Lead foil in air transmission measurement inside Ziess water-phantom without water. Height adjustment is necessary for the different lengths of the applicators. For DR in water measurements, the ion chamber is at a fixed position; the XRS-applicator unit is adjusted up and down for the desirable depth.*

Divergent angle measurement

Repeated inspections of the angle drawn on the printed axial projections of each of the applicator were performed with and without shielding. The divergence was taken to be the angle sustained by the two lines drawn on the penumbra using a protractor. Measurements were repeated three times. The differences were found to be less than ± 2.0°.

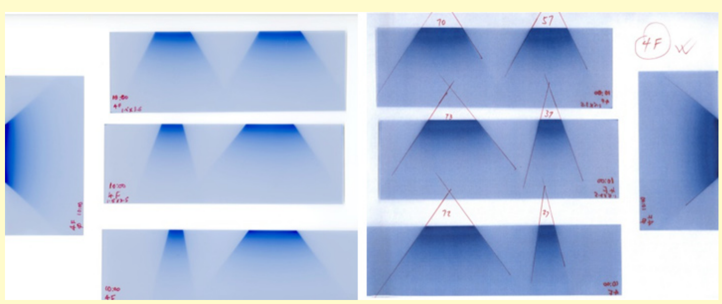


Figure 2b: *DV measurements: Left: Axial projections of open cone and with shielding in place; Right: printed projection with hand drawn divergent lines for measurement with protractor.*

For Equivalent Square investigation

We attempted to apply the general formulae [6] for equivalent square was applied to the DR to the open cones and those of the shielded rectangles. Results are given below.

Results

In-Air Transmission measurement for the lead-foil

The in-air transmission of a single layer of lead-alloy foil is less than 1% (Figure 2b).

As previously indicated, the IFA and ISA have different flattening filters (Figure 3a).

The IFA filter is designed to achieve flat isodose distribution at 5 mm depth. As a result, there is a ring of higher dose at the perimeter up to 5% higher than the central axis at 5 mm depth. (Seen as the "horns" at the 2D scan). The ISF filter is to achieve flat isodose distribution at the surface. Consequently, the isodose profile is less uniform at depths larger than 2mm.

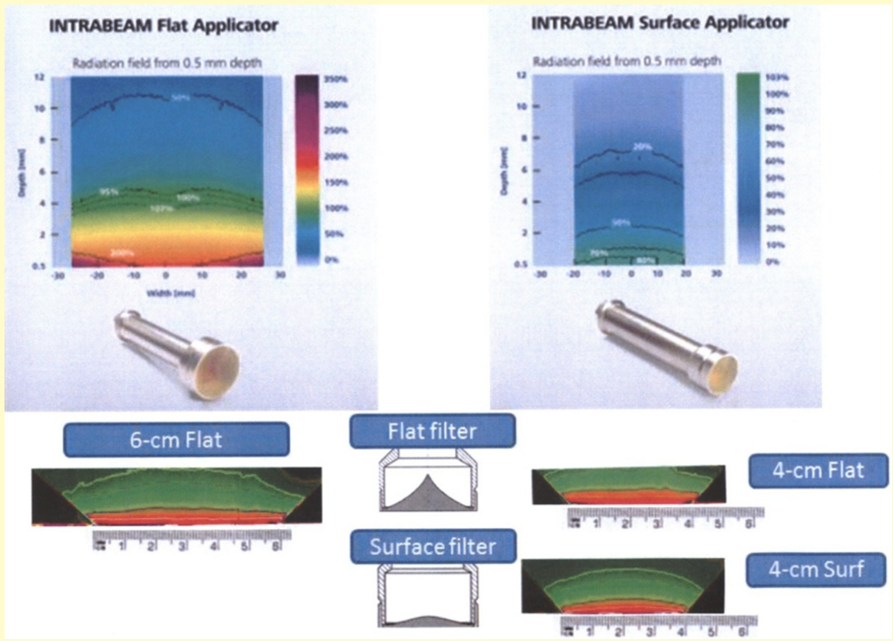


Figure 3a: *Each applicator has a unique flattening filter to achieve isodose flatness in water at specific depth: IFA has a flat isodose curve line at 5 mm; ISA has a flat isodose curve at the surface.*

Dose Rate (DR)

The Soft X-Ray Parallel Plate Chamber is inside the rigid stationary water equivalent chamber of the Zeiss water phantom. (Figure 2c) The closest DR reading starts at 2 mm from the surface of the applicator. Figures 3b show the DR data and Depth Dose curves. The 4 cm IFA open cone DR versus depth curve shows slightly different shape comparing to the 6 cm IFA and 4 cm ISA. We attribute that to the different flattening filter of the 4 cm IFA from that of the 4 cm ISA.

The DR data and Depth Dose curves demonstrate that the smaller cones have higher DR mostly due to the shorter TSD (closer to the virtual target). (6 cm cone IFA, TSD = 25.5 mm; 4 cm cone IFA & ISA, TSD = 21.5 mm.) Between the two 4 cm cones that have identical dimension, the IFA has lower DR compared to those of the ISA due to the extra filtration for the IFA to facilitate flat isodose cures at 5 mm instead being at the surface.

Effects of Shielding on DR

The effect of shielding on the DR was determined by observing the ratio of the shielded DR to the open field (applicator) DR. For the 6 cm IFA (Figure 3b), the general trend is reduction of DR with more shielding and with greater depth. More elongated shielding or collimation has the most DR reduction: up to -30% at 30 mm for the 6 cm with the 1 cm x 3.5 cm cut-out. The least elongated and least shielded or collimated show an increase in DR at 5 mm depth from +1% to +7%.

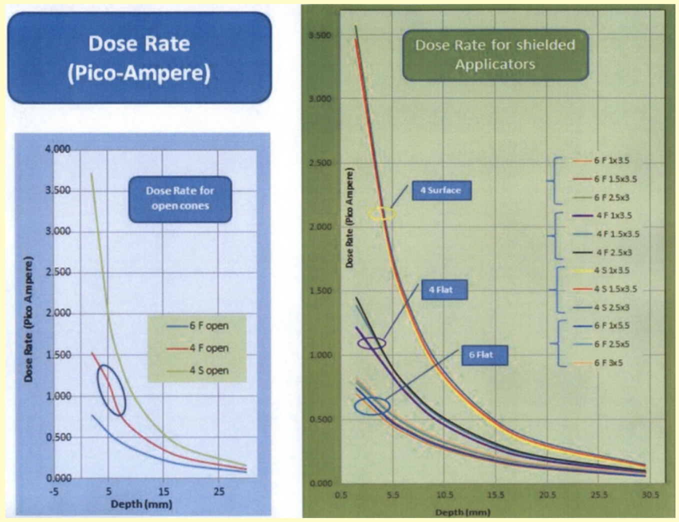
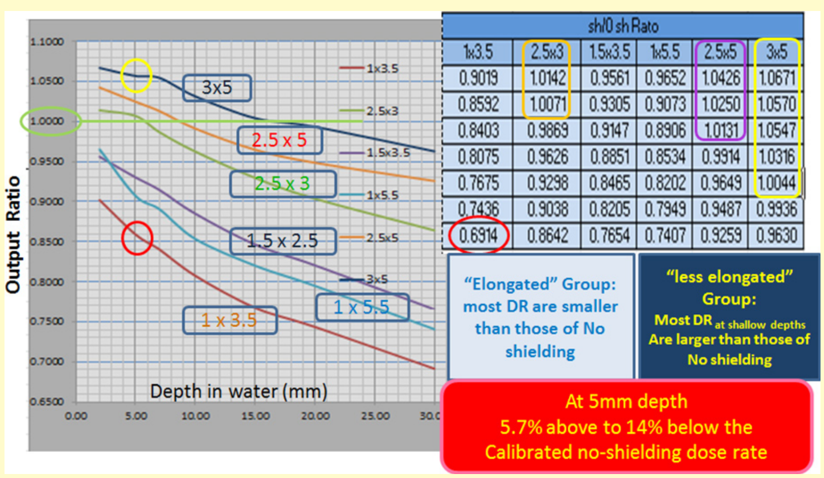


Figure 3b: *Dose Rate versus depth: 6 cm IFA open cone and shielded; 4 cm IFA shielded; 4 cm ISA Shielded.*



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1x3.5	2.5x3	1.5x3.5	1x5.5	2.5x5	3x5
0.9019	1.0142	0.9561	0.9652	1.0426	1.0671
0.8592	1.0071	0.9305	0.9073	1.0250	1.0570
0.8403	0.9869	0.9147	0.8906	1.0131	1.0547
0.8075	0.9626	0.8851	0.8534	0.9914	1.0316
0.7675	0.9298	0.8465	0.8202	0.9649	1.0044
0.7436	0.9038	0.8205	0.7949	0.9487	0.9936
0.6914	0.8642	0.7654	0.7407	0.9259	0.9630

Figure 3c: *DR changes due to shielding for 6 cm IFA.*

The 4 cm IFA and ISA (Figure3d,3e) show similar trend of DR reduction with more shielding and at greater depth. The major differences with these data are the DR build up at the first 5 mm depth, except the least elongated field, 2.5 cm x 3 cm cut-out.

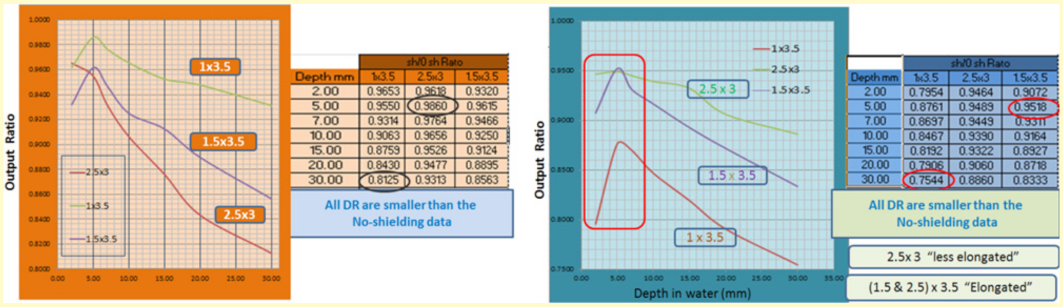

Figure 3d&3e: *Trend of DR reduction with more shielding and at greater depth.*

Percentage Depth Dose

Figure 4, show the PDD based on DR data for the open and shielded cones.

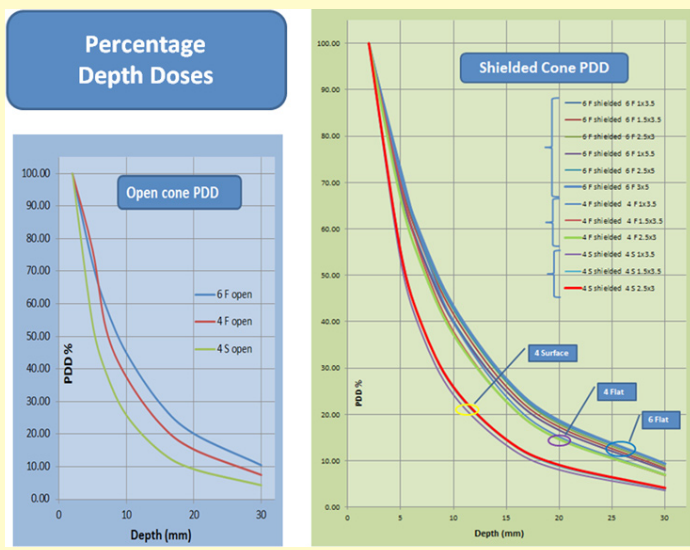

Figure 4: *PDD of open cones and shielded cones.*

Figure 4 shows the PDD for the open cones and each of the cut-out. Nothing particular other than the 4 cm IFA open cone PDD versus depth curve shows slightly different shape comparing to the 6 cm IFA and 4 cm ISA.

Effects of Shielding on PDD

Figure 5 show the ratio of the PDD of the shield field versus the open cone.

The shielding perturbed the PDD of the open cone PDD. Figure 5 demonstrates the variability of the degree of perturbation by the added shielding on the PDD.

The IFA 6-cm cone data displays a general trend of greater differences with increasing depth and increasing elongation of the cut-out shape. At 5 mm depth, the difference varies from 1% to 5% reduction in PDD value.

The IFA cut-out PDD differs from open cone PDD from –6% to +9%; at 5mm there is 0.5% to +8% increases in PDD. The ISA 4-cm cut-outs show -14% to +10% increases in PDD at 5 mm depth. ISA 4-cm cut-outs show -1% to +3% at 5 mm depth. The 4 cm ISA with 1 cm x 3.5 cm cut out shows an atypical inflexion upward at 20 mm.

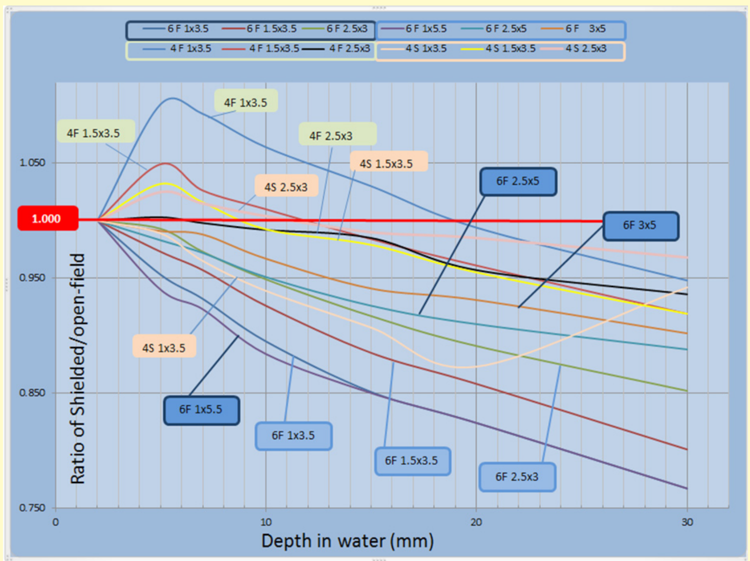

Figure 5: *Ratio of PDD of shielded field versus open field.*

For differentiation graph-label is color coded according to the color show at Table 5.

Divergence

Our manual measurement method tends to cause imprecision. Depending on individual and visual acuity the DV may vary ±2°. However, it yields some general appreciation of the differences using different cone with different cut-outs.

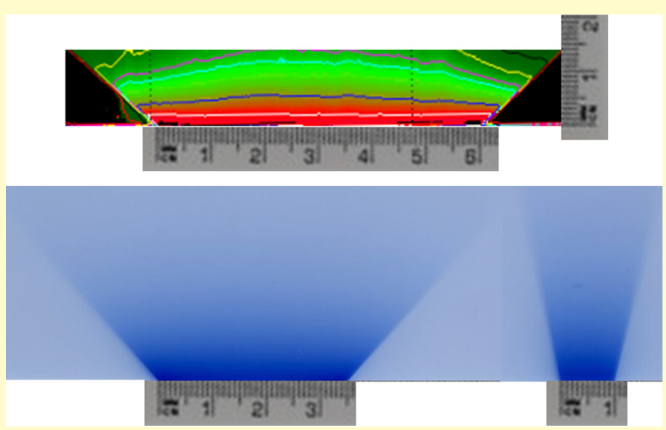

Figure 6: *Top: Enlarged axial projection of the 6 cm ISA open cone. Note the relatively flat isodose line at 2-5 mm depth; the treatment size is larger by about 1.0 cm in diameter. Bottom: 4 cm IFA with 1 cm (right) x 3.5 cm (left) cut-out.*

In general, because of the short TSD and divergence of the radiation area at 5 mm depth is larger than the cone size at the surface or that of the aperture size of the shielding (Figure 6). The smaller the aperture of the shielding the smaller is the DV. The 4 cm cone has shorter TSD than the 6 cm cone, the DV angle of the small cone, has larger DV as compared to the same aperture of the larger cone. IFA and ISA 4-cm cone having the same TSD, yield similar DV with the same shielding.

Table 2 summaries the DV for the different cones and cut-outs.

DA ± 2° Degrees	Open Cone	1x3.5		1.5x3.5		2.5x3	
		1.0	3.5	1.5	3.5	2.5	3.0
4Cm ISA	80	27	71	38	72	58	65
4cm IFA	80	27	72	37	73	57	70
6cm IFA	93	23	67	35	67	54	62
		1x5.5		2.5x5		3x5	
	1.0	5.5	2.5	5.0	3.0	5.0	
6cm IFA		25	88	47	84	61	85

Table 2: *Summary of DA on open cone and shielded cone.*

Equivalent Square Formulation

Equivalent Square prediction for the collimated fields compared to the measured values for the low-KV IORT system does not have any direct correlation to the DR for the series of cones. Failure of the equivalent square approximation is proposed to be the result of four fundamental differences: dissimilar TSD, variable filtration, beam quality variance with field size and scattering contribution from cut-out, and dose rate changes with field size.

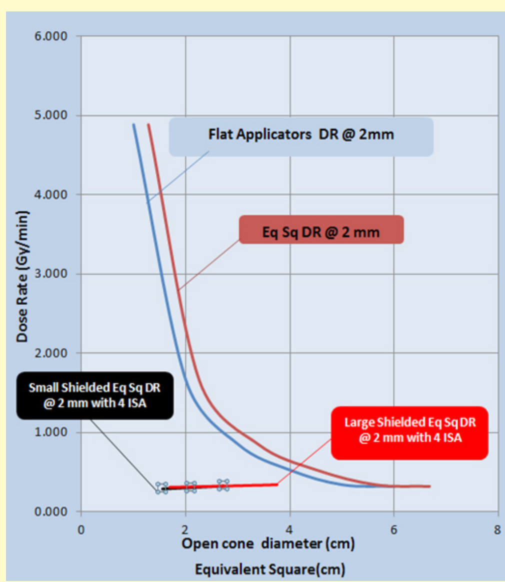

Figure 7: *There is shift of the of the DR curve on the x-axis for the open cone when it is plotted using Equivalent Square of the open cones instead of the open cone diameters. The DR-Equivalent Square graph of the shielded 4 cm ISA has no correlation to the open cone graph.*

Table 4 tabulates the system difference that renders the rule of thumb method unsuitable to predict the data for clinical uses in the low-KV IORT system irregular field treatments.

Equivalent Square Formulation fails with low-KV IORT		
	Equi. Sq. Prediction	**LOW-KV IORT**
TSD	fixed	variable
Filtration	fixed	variable
Beam Quality	slightly variable	significantly variable
	with field-size	with field-size
DR Changes	increase with increased size	increase with decreased size
	(same TSD)	(different TSD)

Table 3: *Factors rendering Equivalent Square Prediction failure.*

Conclusion and Discussion

The commercially available lead alloy foil has less than 1% transmission for the low-KV IORT system. It is found to be suitable for shaping the circular cones to conform to the target shape and area.

Treatment of irregular shaped targets has been simulated with various sizes of circular fields collimated to elongated rectangle. The lead foil shielding field affects the DR by +8% to -30% as a function of the applicator, cutout shape/size/depth. The 6 cm IFA and 4cm IFA have different shielding factors as a function of the cutout size and shape.

The simple "Equivalent Square" method is a poor predictor of applicator output for shielded or collimated treatment fields from the LOW-KV IORT IFA and ISA cones.

The concept may apply to an individual applicator for different shape and size that eliminates the issue of dissimilar TSD, variable filtration and beam quality. Further investigation is in process to establish a table of equivalent square and equivalent diameter or a modified "Sterling" formula, for the largest IFPA applicator and other applicators.

In view of the variance in DR, PDD and DV for clinical application, the irregular shaped field conforming to the target to achieve dose precision within ±5%, the pre-programmed treatment settings for the IFA and ISA requires modification.

The best accuracy is by pre-measurement. However, it may not be practical in routine clinical practice. It would be practical to set up tabulated data for each of the large cone, which may be used for irregular shaping of treatment area with elongated shapes of shields.

The 6 cm IFA DR versus depth characteristics with different shielding is uniquely different from those of the 4 cm IFA and ISA. At a depth of 5mm, the DR difference varies from 6.7% above to 14% below the open cone DR. This implies that there are added scatter in the form of electron or scattered photon at the surface from the lead foil.

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