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Dosimetric Comparison of Superficial X-rays and a Custom HDR Surface Applicator for the Treatment of Superficial Cancers

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Introduction

Superficial cancers are very common and can often be surgically resected but in some cases radiation therapy is preferable due to the patient’s health status, tumor location, and desired cosmetic outcome. Basal and squamous cell carcinomas are most common but Kaposi’s sarcoma, Merkel cell carcinomas, and mycosis fungoides are often able to be treated with superficial radiation as well.

Dose homogeneity and the sparing of healthy tissues are the primary concerns in the management of superficial cancers and as a result the difference in dose at the surface and deepest part of the lesion should be kept to a minimum. For the purposes of this study the superficial region will be defined as shallower than 5 mm. This conservative definition is motivated by dosimetric characteristics of the superficial machine and iridium source which approximate exponential attenuation and inverse square law fall off respectively.

Accelerator produced electrons of energy 4-6 MeV with the addition of a buildup bolus are very well suited for the treatment of shallow lesions as the maximum dose, $D_{\text{max}}$, is brought to the surface. Dose homogeneity in the superficial region, relatively sharp dose fall off, and ability to manufacture custom blocks to spare tissue adjacent to the lesion have made low energy electron the standard of care for most superficial lesions. Electrons depend heavily on a flat treatment surface and placement of bolus but in some regions of the head and neck electron treatments can be difficult to achieve due to placement of bolus and the necessity of sparing deeper critical structures. Very small field sizes can also be a cause for concern due to practical considerations of block manufacturing and dosimetry. In these cases superficial x-rays or HDR surface applicators can take on a role while keeping treatment complexity to a minimum.
Low energy x-rays are a very well established modality and extend over a range of 40-300 kV. The terms associated with this range of energies are usually superficial or soft for 50-150 kV, and orthovoltage for 150-300 kV. The difference in the energies is related to the fall off of dose in water, with the depth dose of the higher energy beams decreasing more gradually as shown in Figure 1. It is important to notice that even at the upper end of the orthovoltage range no skin sparing effect is observed as this effect requires megavoltage energies. Orthovoltage x-rays allow for relatively homogeneous dose distribution to 5 mm depth with the tradeoff of increased dose to deeper structures. Superficial x-rays show less homogeneity in the superficial region and have a percent depth dose (PDD) curve that decreases almost as quickly as radioactive sources.

Figure 1. Percent Depth Dose diagram for various energies
A number of superficial machines have used low energy x-rays for many years to produce excellent outcomes. Most machines are versatile and allow for treatment of circular and square fields of many sizes at multiple source to surface distances. Filtration in the form of aluminum or copper plates can be placed in the beam to preferentially filter out lower energy photons and increase the penetration of the beam.

Although superficial machines are capable and proven in the treatment of skin cancer they are becoming increasingly scare in the clinical environment due to the efficacy of electrons. In many cases treatment by superficial machines would remain preferable due to their ease of use and dosimetric characteristics. While the use of superficial machines has waned, high dose rate (HDR) remote afterloaders have become commonplace and offer low complexity alternatives to electron therapy while providing beam characteristics similar to low energy x-rays.
Literature

A number of application specific HDR applicators have become available as alternatives to electron and superficial cones. Custom dental molds have been designed for this purpose by Parsai et al. (1995) at the University of Toledo Health Science Campus (UT-HSC), formerly Medical College of Ohio, and more recently by Obinata et al. (2007) with many similar papers published in the time between. These papers have show that an experienced team of professionals including radiation oncologist, medical physicist, and dentist can construct custom molds include shielding to spare healthy tissues and reduce the tumor to an easily resectable size and in some cases provide complete tumor control.

Figure 2. Custom dental mold developed at the University of Toledo HSC
HDR applicators have been useful in intraoperative radiation therapy (IORT) cases. In IORT-HDR a Harrison-Anderson-Mick (HAM) applicator can be directly applied to the resected area for treatment. This method has been applied to a number of treatment sites where placement of an IORT electron cone presents challenges. An application of this technique is described by Harrison et al. (1998) involving rectal cancers.

Figure 3. HAM applicator diagram

The use of HAM style applicators for the treatment of superficial skin cancer is very closely related to IORT-HDR and has been studied by a number of groups. The applicator uses the same materials and various sizes are available. In a study by Sabbas et al. (2004) the three superficial modalities are compared and the technical issues of treatment planning with a multi-catheter applicator is examined. Modeled sites included a simple forearm setup and a method of using eye shields under an Aquaplast mask with applicator rigidly attached. A conclusion was reached that with CT based, computer optimized planning HDR HAM-style applicators could provide treatment advantages. Other studies on the topic of external superficial treatments include those done by Svoboda et al. (1995), Guix et al. (2000), and Liebmann et al. (2007) all indicating favorable results and advantages to this type of treatment.
While the flexible HAM style applicator can be effective there are a number of shortcomings. Treatment planning systems are often not capable of incorporating the addition of a lead sheet to the unused side of the applicator and dose homogeneity is not achievable for any plan where dose is desired deeper than the immediate surface. Another style of HDR applicators made of metal to simulate an external beam can greatly simplify treatment planning, setup time, and dose homogeneity problems but is currently limited to field sizes of approximately 7 cm$^2$. Nucletron was the first to make this style applicator for their Microselectron afterloaders.

The Nucletron Leipzig applicator set is comprised of 6 pieces. Aperture diameters of 10, 20, and 30 mm are available and the source can enter either horizontally or vertically. Applicators have also been made for use with the Varian Varisource afterloader, which has a smaller afterloading wire than the Microselectron unit. Much study has gone into the role of the Leipzig applicator in the clinic environment including a study by Ghaly et al. (2006) which only took patients with histologically proven epithelial skin cancers of the face, scalp, and lower extremities and 19 of 21 patients showed complete remission and excellent cosmesis with the remaining two showing partial remission. Evans et al. (1997), Hwang et al. (2003), and Sarudis (2006) have done dosimetric studies of the Leipzig applicator and concluded they can be used as an alternative to electron beam irradiation but must include a thin plastic cap to absorb electron contamination and avoid higher surface doses.
Leipzig applicators lack flatness in the treatment plane due to the isotropic nature of the Ir-192 source. In a paper by Kron et al. (2002) a somewhat roughly designed filter was designed and measured by film. This filter was constructed of 0.2 and 0.88 mm lead foils and showed beam flatness within ± 5% of the central axis dose. The sheets were glued or taped together using double sided tape. Granero et al. (2008) performed a more rigorous study of the tungsten Valentia filter showing improved results. Optimum flattening filter design is discussed by Jeraj et al. (2002) and beam flatness within 1% of central axis dose was shown to be possible.
The objectives of this project are as follows:

I. Characterization of the superficial X-ray unit at 100 kVp, 6mA, with 2mm Al filter using a 2.7 cm diameter glass end cone
   i. In and Cross Plane Beam Profiles using XV film measured at surface and at 5 mm depth with 5.3 cm polystyrene backscatter
   ii. Measurement of SF PDD using CC13 ion chamber, Standard Imaging CDX 2000B electrometer, and small water tank
   iii. Output Dose Rate Measurement for SF Treatment

II. HDR Custom Applicator Design Characterization
   a. Applicator design and manufacturing
      i. Applicator Design
      ii. Design of Plastic Cap for Low Energy Scatter Filtration
      iii. Preliminary Filter Design Based on Open Field Data
      iv. Modified filter, Improving Source Output Characteristics
      v. Secondary Lead Collimator

   b. Ir-192 Radiation Field Characterization for Applicator with plastic cap, applicator with first filter, and applicator with modified filter.
      i. Flatness & symmetry profile using XV at surface, and at 5mm depth with 5.3 cm polystyrene backscatter.
      ii. Dose rate measurements using GafChromic EBT film.
      iii. PDD using GafChromic RTQA film.
      iv. Repeat (i) at surface with lead collimator for the filtered beams.
Materials and Methods

MaximaR 100 Superficial Unit

The MaximaR 100 superficial x-ray machine can be set to 10-100 kV$_p$ by adjusting an analog dial. The tube current can also be adjusted by dial with common currents of 1, 2, and 6 mA being used for filter thicknesses of 0.25, 0.5, and 1+ mm respectively. Various cone sizes are available including glass ended cones with SSD 15 cm and field diameters ranging from 1-4.7 cm and metal cones with SSD 30 cm and diameters 5-20 cm. A glass cone with diameter 2.7 cm was used with 2 mm Al filtration and 6 mA current as the standard the HDR applicator would try to match. This decision was based on the size of an applicator that would be easy to machine, characterize, and handle. This field superficial beam was also used a number of times clinically at the UT Medical Center on neck and lower arm cases.

Output dose rate for the superficial unit was taken during the 2007 annual calibrations using a PTW type TN23342-1579 ionization chamber. This chamber is intended for the range 7.5-100 kV, has a measurement volume of 0.02 cm$^3$, and is within 2% flatness over the intended energy range. Multiple measurements were taken for 60 seconds with the 2.7 cm diameter cone end placed at the surface of the thin detector window. Data for the backscatter factor was obtained from the British Journal of Radiology supplement 25.

Relative PDD (percent depth dose data) was taken using a Scanditronix-Wellhöfer CC13 compact chamber with a Standard Imaging model CDX 2000B in a water tank of dimension 32 × 39 × 40 cm$^3$. The percent depth dose data points were taken at regular intervals to depth 10 cm with a tube potential of 100 kV$_p$ and tube current of 6 mA. Two readings of 60 seconds were averaged for the final result. Beam flatness and symmetry profiles were also taken with film and will be discussed later in this section.
CC13 Compact Chamber

The Scanditronix CC13 User’s Guide (2000) states the CC13 compact chamber is designed for absolute and relative dosimetry of photon and electron beams in air, solid phantom, or water phantoms. It features an air ionization chamber of nominal active volume 0.13 cm\(^3\) which is vented through a waterproof silicon. Both the outer and inner electrodes are made of conducting Shonka C552 air-equivalent material with density 1.76 g/cm\(^3\). The chamber stem is made of PEEK material with density 1.32 g/cm\(^3\). The chamber has a wall thickness of 0.4 mm as well as an inner electrode diameter of 1.0 mm. The cable length is 1.40 m and connects to a TNC triaxial connector. The polarizing voltage is ±300 V with a sensitivity of 3.8 \times 10^{-9} \text{ C/Gy}. The leakage current is defined as less than 4 \times 10^{-15} \text{ A}.

Varian Varisource High Dose Rate Brachytherapy Unit

The Varian Varisource remote afterloading HDR unit uses the VS2000 source model to deliver radiation in close proximity to the desired lesions. The pair of 2.5 mm sources are inserted into the end of a 0.59 mm flexible laser welded wire. The source can be installed with an activity of up to 11 Ci and will decay based on the 73.83 day half life. The source may be positioned up to 150 cm from the afterloader turret with an approximate transit speed of 60 cm/second. The maximum step resolution of the mechanical system is 1 mm and up to 60 dwell positions are possible. Special connectors link the turret to the catheters and significantly reduce the possibility of misconnection errors. Upon closing the turret a locking mechanism aligns the connectors to the reference plan and a sensor sweep is done on the channels to check the status of the connections.
Design of HDR surface applicator

A custom HDR surface applicator was machined out of copper with aperture 27 mm and side collimators of 5 mm giving an overall applicator width of 37 mm. The applicator inner diameter was intentionally made slightly smaller than the 30 mm Leipzig applicator in order to have similar dimensions to the 27 mm aperture cone used on the MaximaR 100 superficial machine. A channel was drilled into the side of the applicator in order to allow the catheter to be horizontally inserted. A slightly deeper catheter channel than usual was incorporated in order to guarantee no travel in the catheter position. This design gave an SSD of exactly 15 mm from the axis of the Ir-192 wire.

The attenuation coefficients for copper over the iridium spectrum are significantly lower than for lead or tungsten. Tungsten alloy was unavailable but would have been preferable to copper due to the added shielding to a theoretical patient. Machining with lead is more complicated and unsafe but a possibility exists for making a mold and then pouring molten lead or cerrobend.
Design of plastic cap

The plastic cap used to absorb low energy scatter in the absence of a flattening filter was made from a piece of polystyrene. The piece of plastic was scanned by a CT and the images were transferred to the Pinnacle treatment planning system. Using the CT density tool the plastic sheet was determined to have an average value of approximately 1070 pinnacle CT units with a density of 1.05 g/cm³. As part of the image import process the Pinnacle TPS will add 1000 to the CT number of the image and delete the remaining negative numbers. This means that the number 1070 displayed by Pinnacle actually corresponds to 70 HU.
Initial flattening filter design

Based on a preliminary RIT X-Omat V film comparison of 100 kV\(_p\) x-rays and the custom HDR applicator a preliminary flattening filter was designed in excel using the attenuation coefficient for copper at the Ir-192 effective energy of 370 kV. The spectrum of Ir-192 is complex and attenuation of all lines will not be equal so a two iteration method was used.

Modified flattening filter design

Based on results from the primary applicator a modified filter was made by attaching thin sheets of shaped lead alloy to the top of the copper applicator. The model 16A-006 lead foil has a thickness of 0.006” and is composed of an alloy of 95.75% lead, 2.5% antimony, and 1.75% tin. Multiple layers of attenuating foil were added to improve beam flatness. The shape of the filter and difficulty in manufacturing appropriately sized foils were limiting factors in the ability to achieve a perfectly flat beam.
HDR Beam Profile

Beam flatness and symmetry of each combination of applicator, filter, and secondary lead collimator were studied using Kodak X-Omat V film. The response of the film to energies in the Ir-192 range was assumed to be acceptable. The flatness response of the film at exposure times of 15, 30, 45, and 60 seconds was studied in order to quantify the relationship between film exposure, and thus optical density, and beam flatness.

Film Processor, Scanner, and Calibration File

The film processor used for developing the X-Omat V films was the Kodak RP X-OMAT processor. Bushberg et al. (2002) describes the operation of the film processor. Film follows a path through a developer, fixer, and wash tank guided by rollers driven at a certain rotation rate by a single motor. After these cycles the film is sent through a drying unit. The Vidar Systems Corporation VXR-16 Dosimetry Pro film scanner was used with RIT v. 5.0 software. A calibration file made at UT-HSC was used to relate optical density to relative exposure for the beam profile scans.

Dose rate measurements using EBT film

Dose rate measurements were necessary to characterize the HDR applicator. The complex spectrum of iridium complicated measurements with ion chambers so different films were compared for energy dependence and dose range suitable for the HDR applicator. GafChromic® EBT film was found to have suitable characteristics for the measurements. A full description of the film, materials, and methods involved in using the film are not the focus of this project and have been included in the appendix.
Percent Depth Dose for HDR applicator

The method used for PDD measurements was motivated by a paper by Schumer et al. (1999) which showed that GaF Chromic film can be useful for measurements of the Ir-192 spectrum and by Kron et al. (2002) whose method is reproduced in this paper. Measurements were taken for the applicator with plastic cap and also for the final filtered beam with collimator by sandwiching a sheet of GaF Chromic film between two vertical slabs of 5.3 cm thick water-equivalent backscatter. Care was taken to make sure the film edge was flush with the backscatter surface and perpendicular to the face of the applicator. The film was then processed in RIT 5.0 and isodose distribution generated in order to verify the ionization chamber measurements.

The film type used for the PDD measurements was GafChromic® RTQA. Thomas and Warrington (2006) describe the use of RTQA type film for QA measurements. The study of RTQA film shows the film is not suited for absolute dosimetry but is relatively energy independent. For this purposes of percent depth dose only a relative, qualitative comparison is necessary.
Results

Figure 9. Beam profile as a function of exposure

(a) Beam profile for 15 second exposure

(b) Beam profile for 30 second exposure
(c) Beam profile for 45 second exposure

(d) Beam profile for 60 second exposure
Superficial Unit

Figure 10. Superficial Beam Profile at Surface

Figure 11. Superficial Beam Profile at 5 mm Depth
Output Dose Rate

The equation for Dose Rate in cGy/min is given by:

\[
\dot{D} = 0.92 \cdot M_{\text{raw}} \cdot N_s \cdot C_{t,p} \cdot BSF \cdot K_Q = 200.23 \text{ cGy/min}
\]

where \( M_{\text{raw}} \) is in nC, \( N_s \) is R/nC, and 0.92 cGy/R is the factor relating exposure to dose. Two readings of \( M_{\text{raw}} = 1.48 \times 10^{-8} \) C were each recorded over a period of 1 minute for the raw ionization. \( C_{t,p} = \frac{P_{\text{ref}}}{P} \frac{T + 273.2}{295.2} C \) = 1.01391 based on a temperature of 21.5 C and a pressure of 750.8 mmHg. The backscatter factor (BSF) was taken from interpolated values of the BJR supplement 25 and was found to be BSF = 1.13. \( K_Q = N_{D,w}^{Q_{\text{Co}}}/60 \) Co_{N,D,w} = 0.9822 is the quality conversion factor relating the quality of the beam to Co-60.
Figure 13. $K_Q$ vs. aluminum thickness

\[ y = 0.0024x^2 - 0.0172x + 1.0066 \]

HDR Applicator

Figure 14. Surface profile of HDR applicator with plastic cap
Figure 15. Profile at 5 mm depth for applicator with plastic cap

Figure 16. Comparison of in-plane and cross plane profiles for HDR applicator
Figure 17. Surface profile for applicator with plastic cap and lead collimator

![Surface profile for applicator with plastic cap and lead collimator](image1)

Figure 18. Percent depth dose for applicator with plastic cap

![Percent depth dose for applicator with plastic cap](image2)
Figure 19. Surface profile for applicator with primary filter

Figure 20. Profile at 5 mm depth with primary filter
Figure 21. Surface profile for primary filter with lead collimator

Figure 22. Surface profile for applicator with modified filter
Figure 23. Profile at 5 mm depth for applicator with modified filter

Figure 24. Surface profile for modified filter with lead collimator
Figure 25. Percent depth dose for applicator with modified filter

Table 1. Superficial cone and HDR applicator dose rate

<table>
<thead>
<tr>
<th></th>
<th>Dose Rate (cGy/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial 100 kVp</td>
<td>200.23</td>
</tr>
<tr>
<td>Applicator &amp; Cap</td>
<td>147.25</td>
</tr>
<tr>
<td>Primary Filter</td>
<td>113.0</td>
</tr>
</tbody>
</table>
Discussion

The relationship between exposure and flatness was tested in Figure 9a-d. The results show little deviation over different exposure times ranging from 15 to 60 seconds. Minor differences can result from a number of factors including developing errors, changes in applicator orientation, and minor differences in the extension distance of the iridium source. Based on these four tests an exposure time of 30 seconds was chosen. All beam profile films were shot at the same time to avoid any error introduced by the decaying source.

Due to the construction of the applicator some asymmetry was expected. Commercial Leipzig applicators attempt to resolve this issue by having the source enter from a slot on the top of the applicator. Despite the source being longer along the axis of the catheter, Figure 16 shows little difference in cross plane vs. inline profile. The beam profile becomes slightly less homogenous for the modified filter which lacks exact radial symmetry.

One of the attractive points of the HDR applicator was the inverse square fall off of dose with depth. Figures 18 and 25 show the applicator with plastic cap and modified filter respectively. For the plastic cap the dose fall off is nearly the same for the superficial cone and the HDR applicator. For the case of the modified filter the HDR falls off slightly faster from the surface to 2.5 cm depth then falls off less rapidly than the superficial cone. This data shows that the HDR applicator must be treated as an exponential decay rather than an inverse square fall off and little addition sparing effect will be observed for tissues deep to the target for the HDR applicators.
Results for beam width and field flatness are displayed below in Table 1. The full width at half maximum (FWHM) is a measure of beam profile, which is described by the 50% isodose line. The field flatness is measured at the nominal field edge of 1.35 cm. The number chosen for field flatness reflects the maximum deviation across the field for each beam.

Table 2. Comparison of beam characteristics

<table>
<thead>
<tr>
<th></th>
<th>FWHM (cm)</th>
<th>Flatness (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial (0 mm)</td>
<td>2.96</td>
<td>± 5</td>
</tr>
<tr>
<td>Superficial (5 mm)</td>
<td>3.1</td>
<td>± 5.5</td>
</tr>
<tr>
<td>Plastic Cap (0 mm)</td>
<td>3.56</td>
<td>± 27</td>
</tr>
<tr>
<td>Plastic Cap (5 mm)</td>
<td>4.68</td>
<td>± 19</td>
</tr>
<tr>
<td>Plastic Cap + Pb</td>
<td>3.46</td>
<td>± 10</td>
</tr>
<tr>
<td>Filter (0 mm)</td>
<td>4</td>
<td>± 19</td>
</tr>
<tr>
<td>Filter (5 mm)</td>
<td>5.1</td>
<td>± 19</td>
</tr>
<tr>
<td>Filter + Pb</td>
<td>3.98</td>
<td>± 7.5</td>
</tr>
<tr>
<td>Mod filter (0 mm)</td>
<td>4.1</td>
<td>± 8</td>
</tr>
<tr>
<td>Mod filter (5 mm)</td>
<td>5.3</td>
<td>± 9.5</td>
</tr>
<tr>
<td>Mod filter + Pb</td>
<td>3.7</td>
<td>± 8.5</td>
</tr>
</tbody>
</table>

Table 2 allows a grounds for the beams to be compared. This project was based on the superficial cone and HDR applicator of inner diameter 2.7 cm. By the standards of the table an ideal beam would have a FWHM of 2.7 cm at both the surface and at depth 5 mm. An ideal beam would also show ± 0% deviation in flatness across the beam profile. A beam with no divergence and a perfectly sharp field edge are physically impossible and so a more practical comparison uses the superficial machine as the gold standard the HDR applicator data attempts to mimic.
The superficial cone shows little beam divergence widening from 2.96 to 3.1 cm from the surface to 5 mm depth. The HDR applicators show a much larger divergence between the surface and 5 mm depth. The lead collimator does help to tighten the beam profile at the surface with the most pronounced improvement occurring for the modified filter. Should the applicator be used for treatment the increase in lateral dose should be noted.

Beam flatness with the combination of plastic cap and applicator deviates significantly from both an ideal beam profile and the actual superficial cone profile. The application of a preliminary filter showed some improvement but it was not until the modified filter that a deviation of ±8% approached the ±5% flatness of the superficial cone. Measuring beam deviation at depth is a slightly grey area since all beams must diverge. There is not a one to one correspondence between the superficial cone and HDR applicator due to the differences in SSD and collimation, thus comparing the beam flatness at 5 mm depth should be done with caution.

The backscatter effects of the secondary lead collimator are significant and can make the HDR applicator have an acceptable beam profile and deviation without the addition of any flattening filter. If this combination were to be used care should be taken to place the plastic cap between the lead collimator and patient’s skin to avoid the low energy scatter which would be introduced by the high Z lead. The effects of collimation on beam profile are demonstrated in Figure 21 where the dose is seen falling off abruptly at the nominal field edge. In this case the lead collimator is designed to match the inner and outer diameter of the copper applicator.
Using a thicker collimator would sharpen the beam profile to the point of the superficial cone and would improve the beam flatness due to the increased SSD. A negative effect of increased lead collimation would be a lower dose rate and slightly larger scatter peaks at the edge of the field.

Measurements with GafChromic EBT film showed a dose rate of 147.25 cGy/min for the applicator with plastic cap and 131.0 cGy/min for the applicator with primary filter. These dose rates reflect the central axis dose rate which is the maximum dose rate the applicator achieves at the surface. At the time of measurement the treatment strength of the source was 21652.31 cGy cm$^2$/h. For the applicator and cap at a distance of 1.6 cm and over the period of 1 minute a dose of 141 cGy would be expected for a source alone. Assuming a perfect film measurement 4.4% increase in dose would be due to increased scatter from the copper applicator and backscatter from the 5.3 cm of polystyrene.
Conclusion

The goals of this project were to characterize a frequently used superficial cone size and compare it to a custom designed HDR applicator with plastic cap. The applicator was intended to achieve the same beam profile and have a more rapid dose fall off. Based on the initial beam profile it was necessary to design two flattening filters to shape the HDR beam profile.

Beam profile measurements showed improvement with each successive filter added. The beam profile for the modified filter approached the superficial unit within 5% at the surface but diverged significantly as depth increased. Lead collimators introduced a significant amount of scatter to the field at the surface which helped remove the need for a flattening filter. The significant effect of the lead collimator on the applicator beam suggests further study. Monte carlo simulations of different collimator dimensions could determine whether a flattening filter is actually a necessary component to the custom HDR applicator.

Central axis dose rate measurements showed a higher dose rate for the superficial unit at the surface. Treatment times with HDR surface applicators would remain under 90 seconds in most cases.

This project has shown that design and characterization of a custom HDR applicator is both practical and a low cost alternative to commercial products. An acceptable beam profile can be achieved and the treatment time will remain similar to the traditional superficial x-ray unit. Furthermore, treatment planning consists of a simple dose rate calculation and little possibility for setup error exist making the correctly characterized HDR applicator a safe treatment option for the patient.
References


Abstract

The purpose of this study was to design and characterize a custom HDR applicator for the treatment of cancers in the region 0-5 mm, comparing it to the dosimetric properties of the MaximaR-100 superficial x-ray unit. The superficial machine was characterized in terms of percent depth dose, beam profiles, and dose rate and similar measurements were taken for the copper HDR applicator. The applicator alone had an unacceptably large dose inhomogeneity across the beam so a primary filter, modified filter, and secondary lead collimator were designed and manufactured to help shape the dose into a profile similar to the superficial applicator. Beam flatness and width were nearly replicated but beam divergence was more pronounced for the HDR applicators. Percent depth dose measurements for the HDR applicator showed a dose fall-off nearly identical to superficial x-rays rather than the assumed inverse square dose fall-off.
Appendix

Dosimetry using GafChromic EBT film

Information from this section was derived from the white paper on EBT film available at www.gafchromic.com. Many types of film are available for absolute dosimetry but GafChromic EBT Radiochromic film has been shown to be a very competitive film with the additional benefit of developing without a processor. EBT is 10 times more sensitive than the previous HS and MD-55 films and has improved uniformity from 8% to better than 1.5%. The dose sensitivity of this film is 2 cGy – 800 cGy, which falls in the range of values clinically practical for this project. The spatial resolution is > 5,000 dpi, which is sufficient for a dose rate measurement. Cutting and marking the film do not affect its properties.

The film is made by laminating two coatings. Each laminate has a slightly different thickness and is differentiated by a batch number. Each separate batch of film must be treated as a different film and requires recalibration. Figure A1 shows a schematic of the polyester laminate, active layer, and surface layer. The active layer is made of a material which turns blue in a polymerization reaction initiated by irradiation.

Figure A1. Construction of EBT Film showing polyester, active, and surface layers

| CLEAR POLYESTER - 97 microns |
| ACTIVE LAYER - 17 microns |
| SURFACE LAYER - 6 microns |
| ACTIVE LAYER - 17 microns |
| CLEAR POLYESTER - 97 microns |
A dose rate measurement of Ir-192 requires a film that is energy independent over the kV to MV range. Figure A2 shows the energy dependence of EBT film over the range 30 kV$_p$ to Co-60 energies. Data from ISP shows a deviation of less than 5% between keV and MeV photons. Further work by Butson et al. (2006) shows a deviation of less than 10% over the range 50 keV – 50 MeV. In addition to allowing uniform measurement of the Ir-192 spectrum energy independence allows a calibration curve to be quickly and reliably made with an accelerator using 6 MV photons and applied to nearly any measurement of dose in the clinical environment.

Figure A2. Energy dependence in the range 30 kV$_p$ – 1.25 MV
Figure A3. Energy dependence in the megavoltage region

Measurement of EBT film can be done with transmission densitometers, film scanners, and spectrophotometers. For this project the Vidar VXR-16 Dosimetry Pro was used. The blue colored polymer has an absorption maxima at 636 and 585 nm. EBT film is most responsive to measurement with red light.

Figure A4. Absorption spectrum of EBT and HS film
During the manufacturing of EBT film the active needle-like components of length 15-25 μm and diameter 1-2 μm tend to align with their long axis parallel to the coating direction. More light scatters perpendicular to the coating direction resulting in increased amounts of light collected by the system when the films are scanned with short edge to the scanner ie. landscape mode. Care must be taken to mark the film to describe the orientation at the time of calibration.

Figure A5. Orientation dependence of EBT film

Post irradiation density growth is a concern in the measurement of dose with EBT film. Figure A6 shows a number of important EBT density growth characteristics. The density growth is less significant for lower doses which works well for the measurements in the range of 25 – 500 cGy for this project. The density growth is almost entirely complete after a period of 48 hours but can be approximated as complete 2 hours after exposure. Measurements for this project were taken over 48 hours after exposure and should introduce little density growth error.
Additional considerations exist for EBT dosimetry and whenever possible the most strict standards were applied. EBT film has demonstrated a small response to white light so all films were kept in an envelope separated by sheets of provided tissue cloth when not in use. Handling of films was done as carefully and minimally as possible using gloves to keep oils off the films. The scanner was calibrated for scan field flatness to reduce scanner uniformity errors.

Development of Calibration curve

The OD calibration is used to plot an H&D data and analyze sensitometry data.

The first step in developing a curve to relate optical density (OD) to A/D value is to scan a step wedge profile. A region of interest (ROI) is drawn across the wedge profile and cropped. For this project the HOWTEK H724 step wedge was used. The specific step wedge is not as
important as correctly associating the ODs on the specific step profile. After cropping the ROI the software was instructed to get the step wedge values. This finds the number of steps and for the Vidar 16 bit scanners 28-31 steps are usually found, 29 valid steps were found. The OD values for each step were manually entered based on the data provided with the step wedge film.

After irradiating the films to the doses described in Table A2 the films were placed with their orientation dots in the bottom right hand corner of a film scanning template. ROI boxes were centered on each of the films and dose values entered to correspond to the pixel values in the ROI. At this point one would generally associate the step wedge and have a calibration file made but it is more straightforward to make a plot of pixel value vs. dose in an Excel spreadsheet.

**Measurements**

**Table A1. Step wedge calibration data for H724 sheet**

<table>
<thead>
<tr>
<th>Step</th>
<th>OD</th>
<th>Step</th>
<th>OD</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.11</td>
<td>18</td>
<td>1.86</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>19</td>
<td>1.97</td>
</tr>
<tr>
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<td>20</td>
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<tr>
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<td>0.35</td>
<td>21</td>
<td>2.23</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
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<tr>
<td>10</td>
<td>0.9</td>
<td>26</td>
<td>2.91</td>
</tr>
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<td>1</td>
<td>27</td>
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</tr>
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<td>32</td>
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<tr>
<td>17</td>
<td>1.72</td>
<td>33</td>
<td>3.77</td>
</tr>
</tbody>
</table>
A minimum of 13 exposures are suggested to develop an accurate calibration curve.

The films listed below were exposed at 6 MV on the Elekta SL-25 at 100 SSD using 5.3 cm of backscatter and 1.3 cm of buildup. Radcalc was used to calculate the necessary monitor units.

Table A2. Film dose table

<table>
<thead>
<tr>
<th>Film #</th>
<th>Dose (cGy)</th>
<th>Pixel Value</th>
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</thead>
<tbody>
<tr>
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<td>43589</td>
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<td>25</td>
<td>39317</td>
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<td>35446</td>
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<td>4</td>
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<td>25638</td>
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<td>20200</td>
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<td>15660</td>
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<tr>
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<td>14263</td>
</tr>
<tr>
<td>12</td>
<td>500</td>
<td>13733</td>
</tr>
<tr>
<td>13</td>
<td>550</td>
<td>12636</td>
</tr>
</tbody>
</table>

Figure A7. A/D Value vs. Dose

\[ y = -0.0003x^3 + 0.3444x^2 - 162.43x + 43182 \]
The equation in Figure A7 describes A/D value (pixel value) vs. dose in cGy.

\[ y = -0.0003x^3 + 0.3444x^2 - 162.43x + 43182 \]

A third order polynomial was used and fit the data points nicely. Given A/D values the dose must be solved for numerically which was also easily done in Excel. The pixel value for the combination applicator & plastic cap was \( y = 25773 \) which corresponded to a dose of 147.25 cGy in one minute. For the primary filter \( y = 28793 \) which corresponded to a dose of 131.0 cGy in one minute.