Addressing the Challenges of Using a Titanium Applicator with a Low-Energy Brachytherapy Source

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Outline

- Introduction
  - Electronic brachytherapy sources
  - Xoft Axxent® source
  - Challenges
- Methods
  - Formalism
  - Measurements
  - Monte Carlo simulations
- Results
  - Dose-rate conversion coefficient
  - Azimuthal anisotropy
  - Radial dose function
  - Polar anisotropy
- Conclusions
- Future work

Outline

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  - Xoft Axxent® source
  - Challenges
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Electronic brachytherapy sources

- Delivery of low energy radiation at high dose rates
- Three sources currently being marketed
  - Elekta Esteya®[1]
    - Developed for the treatment of skin lesions
  - Zeiss INTRABEAM[2]
    - Developed for intraoperative radiotherapy
  - Xoft Axxent® source[3]

http://www.esteya.com/

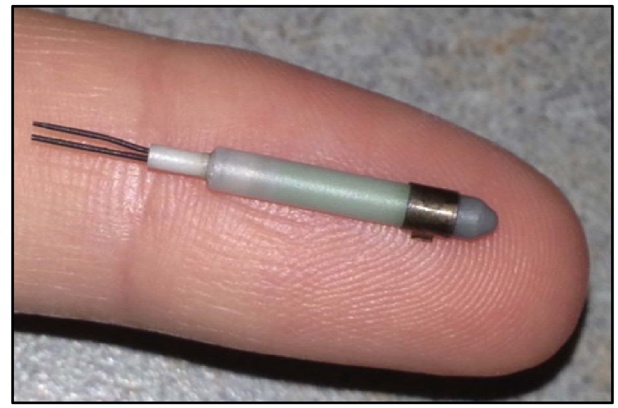
http://radonc.ucla.edu/site.cfm?id=458

openi.nlm.nih.gov/detailedresult.php

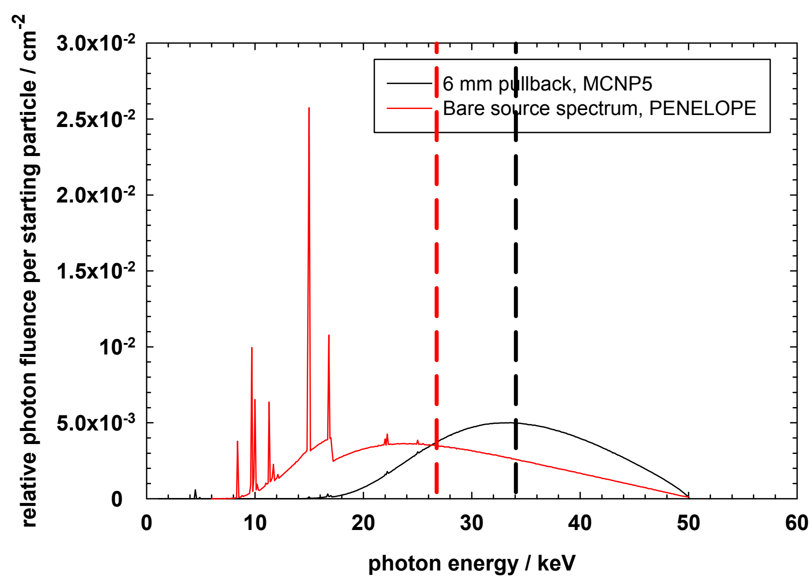
1. Elekta, Stockholm, Sweden
2. Carl Zeiss Surgical, Oberkocken, Germany
3. Xoft Inc., a subsidiary of iCAD, San Jose, CA

Xoft Axxent® x-ray source

- Operated at 50 kVp and 300 μA
- Produces a lightly-filtered bremsstrahlung spectrum
  - Mean energy of the bare source is 26.6 keV at 50 kVp
- FDA approval:
  - Breast, vaginal cuff, skin, cervix
- Titanium cervical applicator
  - Introduces a significant heterogeneity effect
  - Hardens the bremsstrahlung spectrum
  - Modifies the dose distribution



Xoft source outside of cooling catheter



1. Davis, S. D. (2009). Air-kerma strength determination of a miniature x-ray source for brachytherapy applications. Ph.D. dissertation, University of Wisconsin-Madison.

Challenges and research plan

1. NIST traceability
   - Establishment of an air-kerma rate standard
   - Standard was transferred to the UWADCL
2. Applicator introduces heterogeneity
   - Modified TG-43 dosimetry formalism
3. Impact of applicator-to-applicator variations on the dosimetry parameters due to manufacturing tolerances
   - Measurements with multiple applicators to develop representative dataset
4. Dosimetry dependence on applicator geometry
   - Development of multiple dosimetry datasets

Outline

- Introduction
- Methods
  - Modified formalism
  - Experimental techniques
  - Monte Carlo simulations
- Results
- Conclusions
- Future work

Modified TG-43 formalism

TG-43U1

$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_P(r,\theta)}{G_P(r_0,\theta_0)} \cdot g_P(r) \cdot F(r,\theta)$$

Modified Formalism

$$\dot{D}(r,\theta) = \dot{K}_{50\ cm} \cdot \chi_i \cdot \frac{1}{r^2} \cdot g_i(r,\theta) \cdot F_i(r,\theta)$$

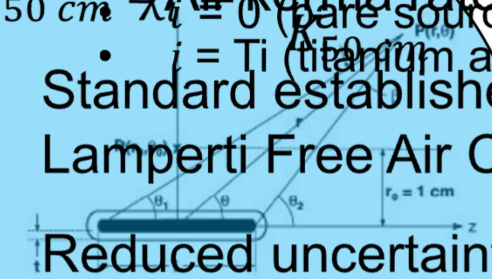
$\dot{K}_{50\ cm}$ = Air kerma rate at 50 cm in air

- Standard established at NIST using the Lamperti Free Air Chamber
- Reduced uncertainty of the measured value

$$\chi_i = \frac{\dot{D}_i(r_0,\theta_0)}{\dot{K}_{50\ cm}}$$

i = applicator identifier

- i = 0 (bare source)
- i = Ti (titanium applicator)



DeWerd et al., “A modified dose calculation formalism for electronic brachytherapy sources,” Brachytherapy, accepted for publication (2015).

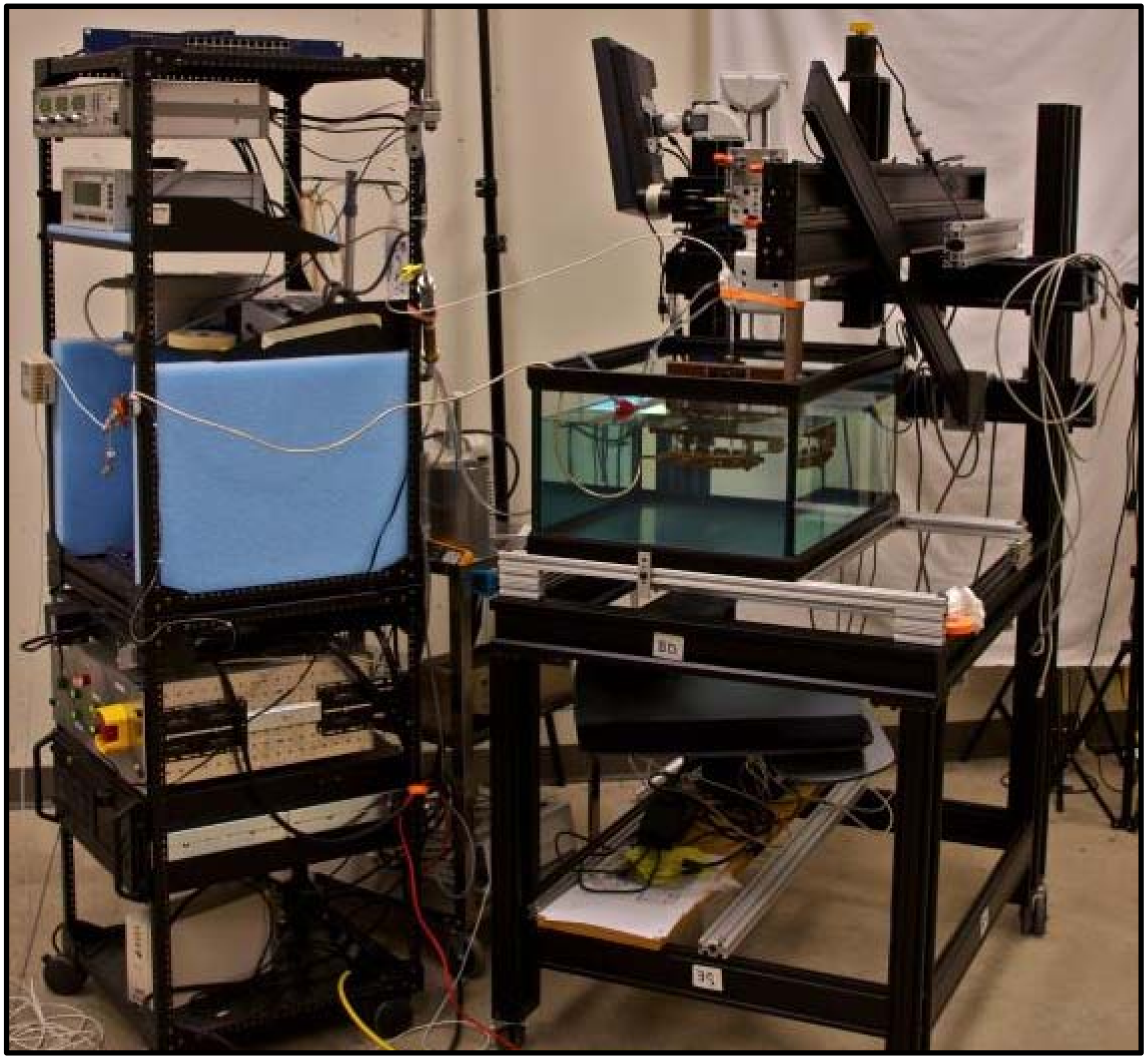
Well chamber

- Measurements performed:
  - Before and after TLD measurements
- Method the UWADCL uses for transferring the NIST standard to clinical well chambers
- Insert designed at UWMRRC to accommodate Xoft Source[2]

HDR 1000 Plus well chamber[1]

1. Standard Imaging, Middleton, WI
2. Davis, S. D. (2009). Air kerma strength determination of a miniature x-ray source for brachytherapy applications. Ph.D. dissertation, University of Wisconsin-Madison.

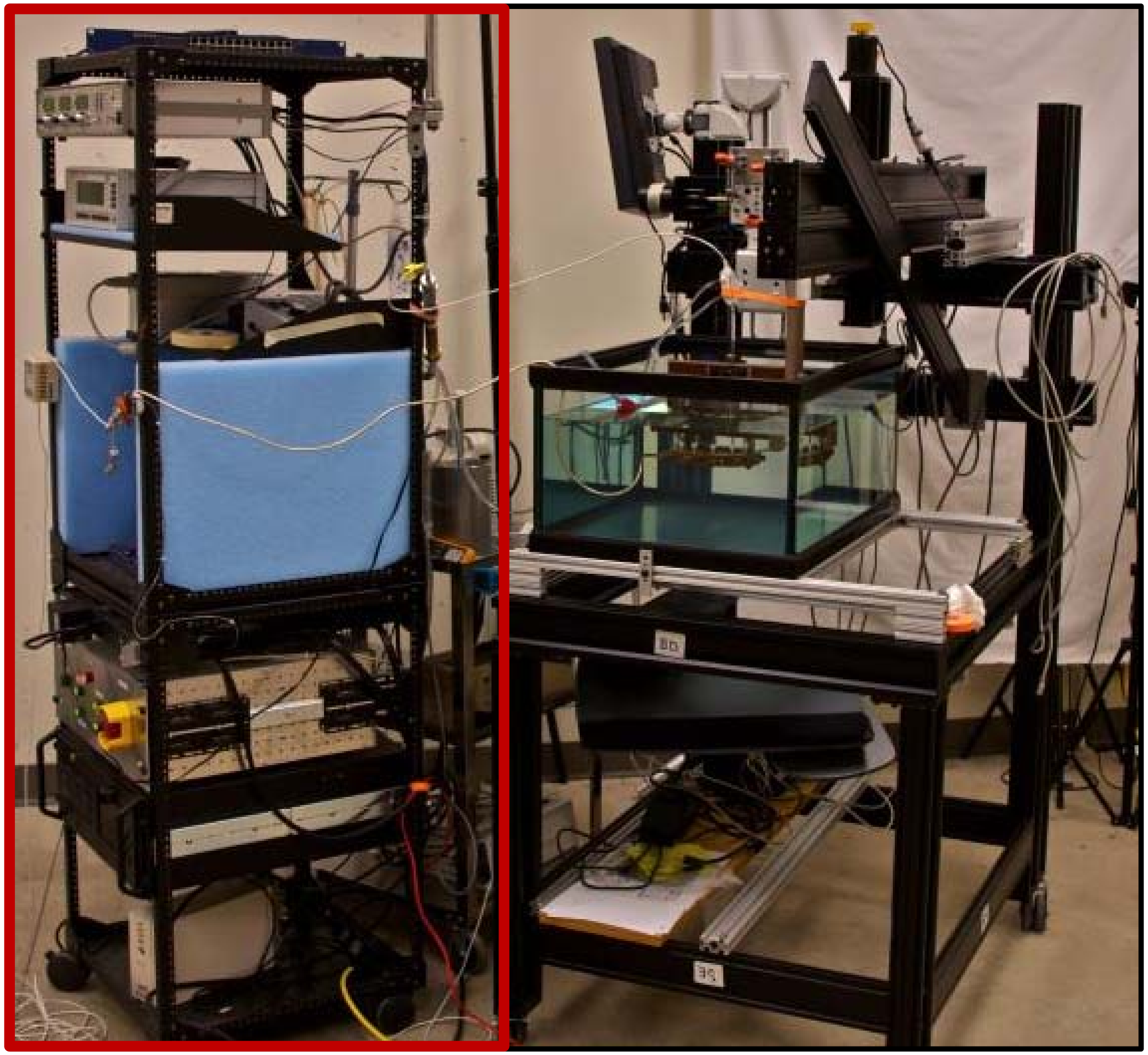
Experimental Setup



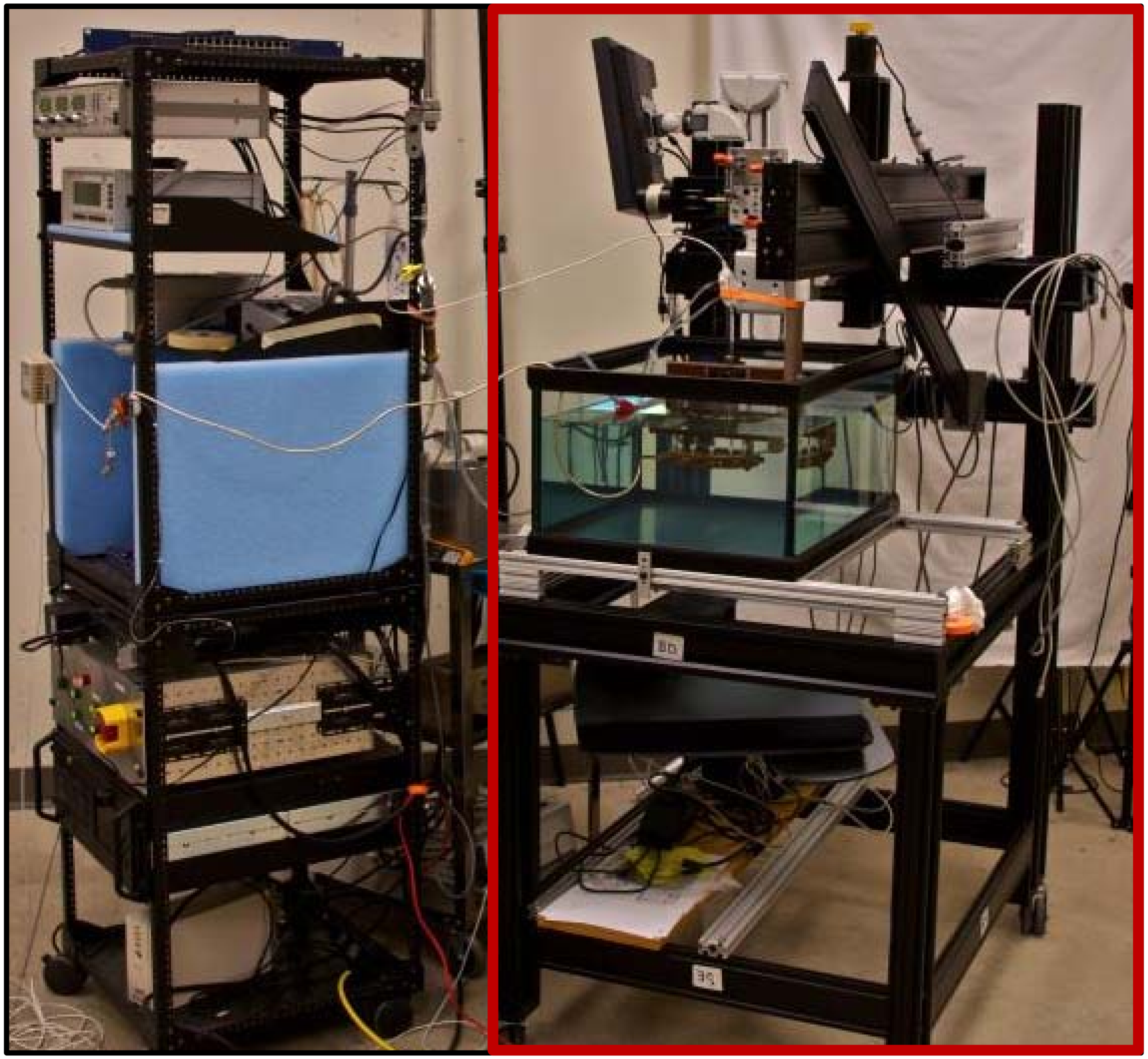
Experimental Setup

- Introduction
- Methods
- Results
- Conclusions
- Future work

Manufacturer Test Fixture

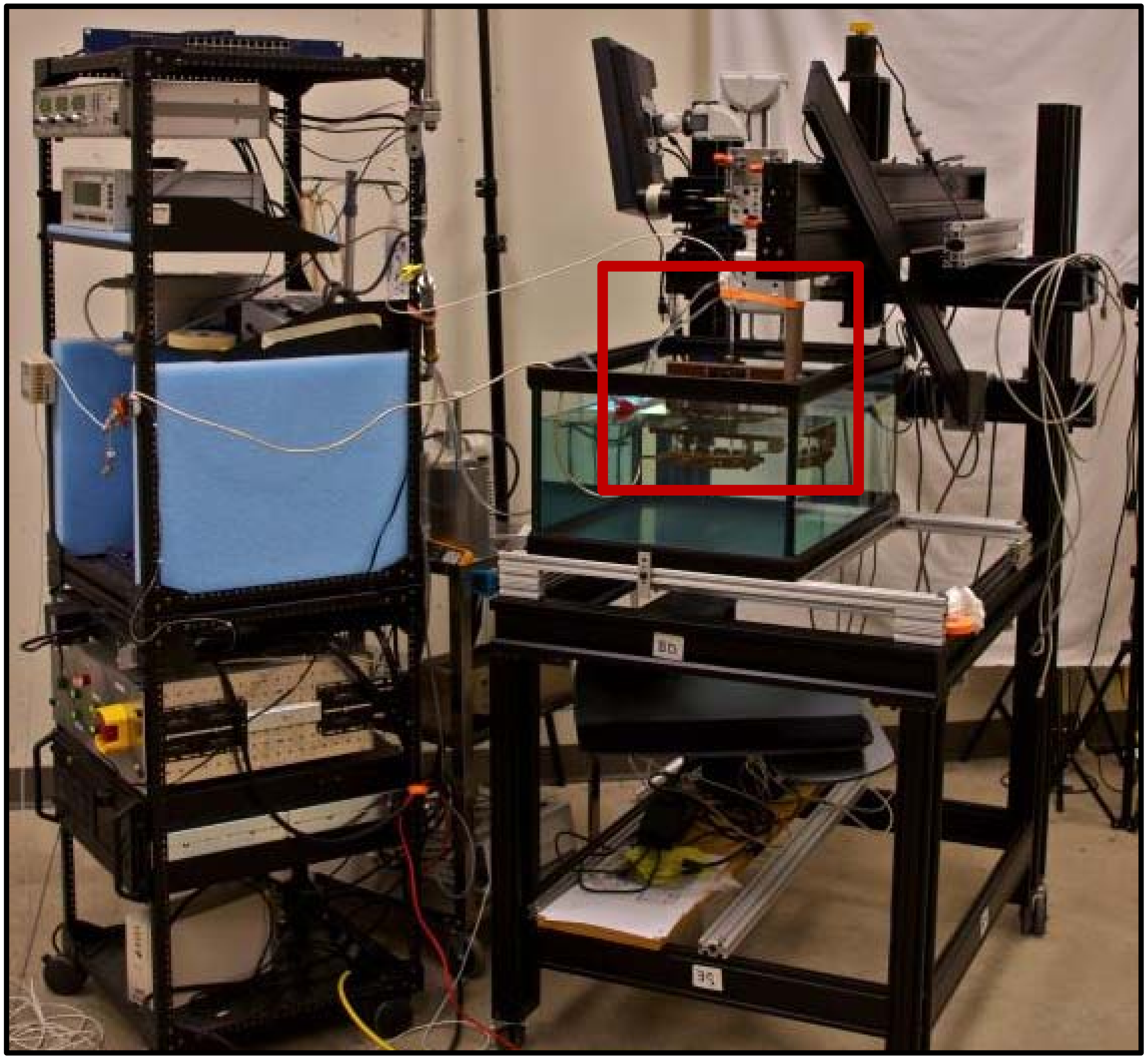


Experimental Setup



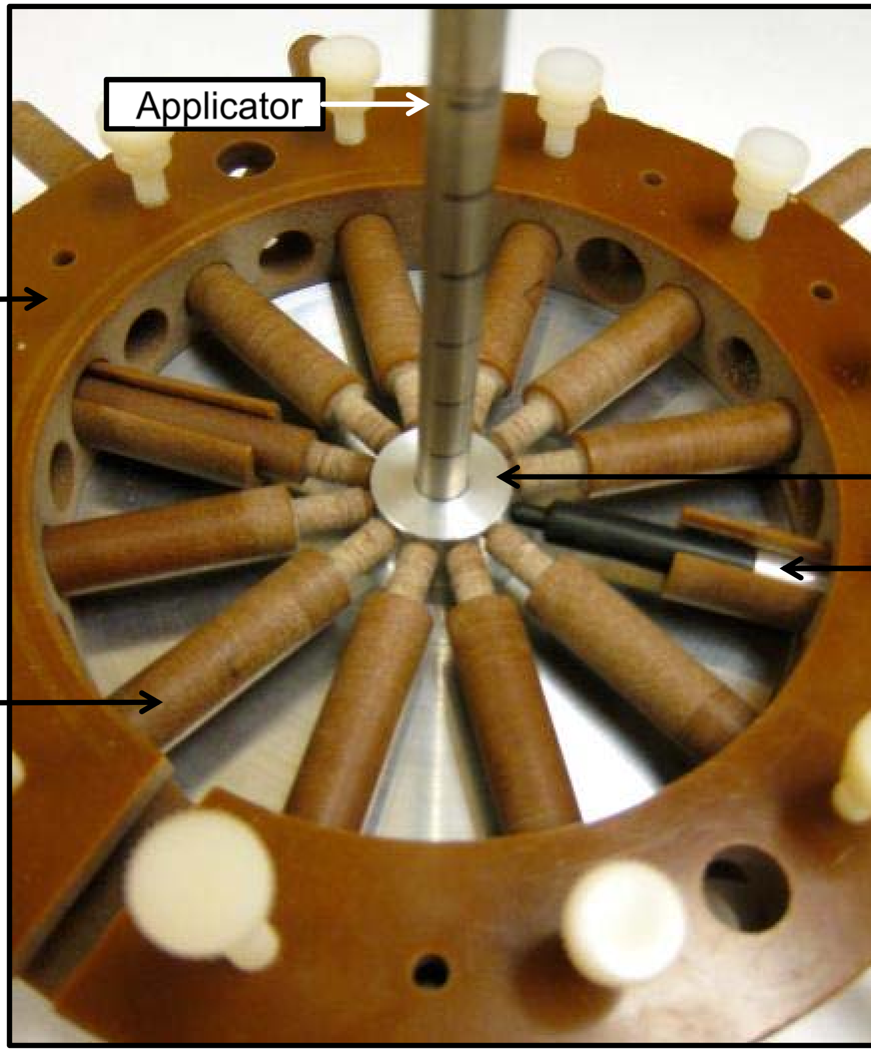
Water Phantom

Experimental Setup



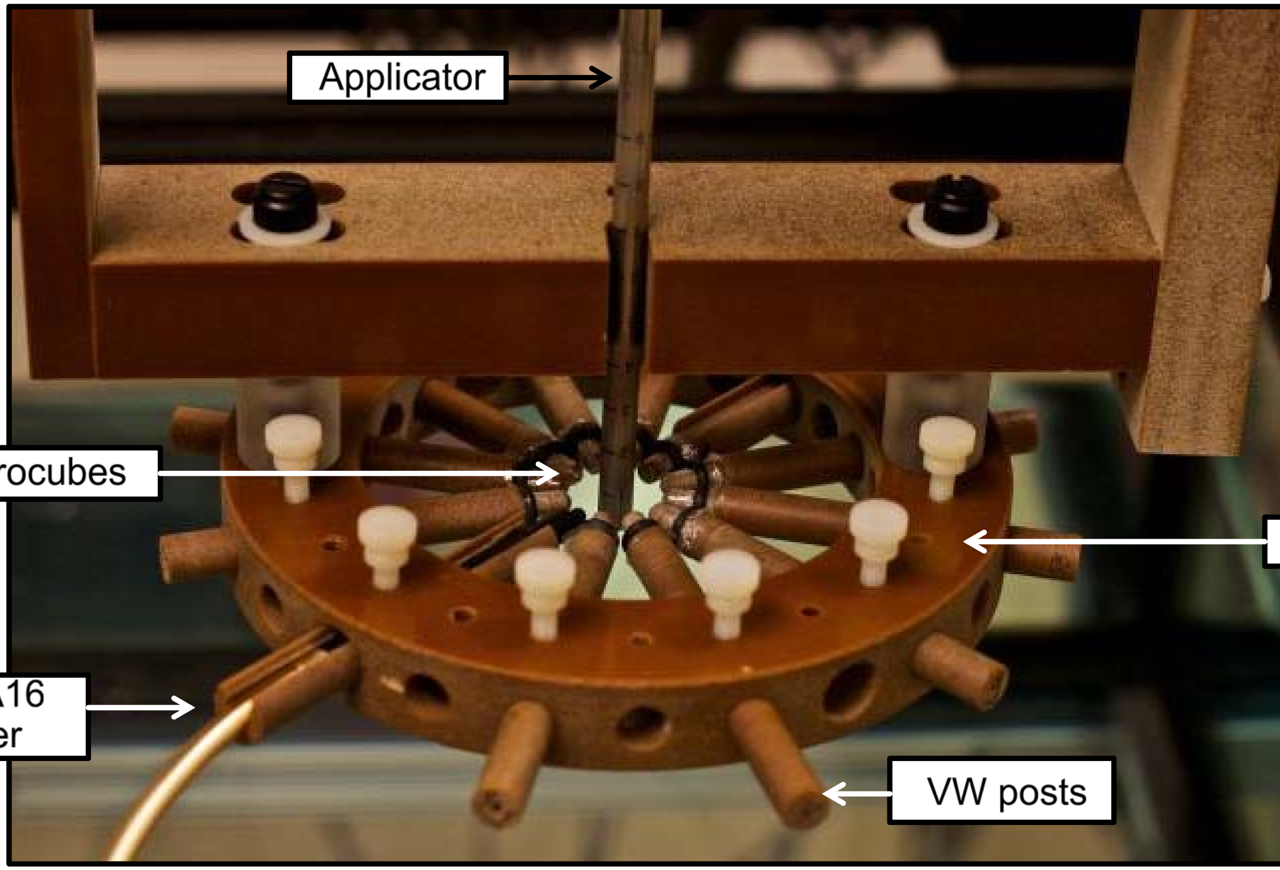
Captain's Wheel

Captain's Wheel



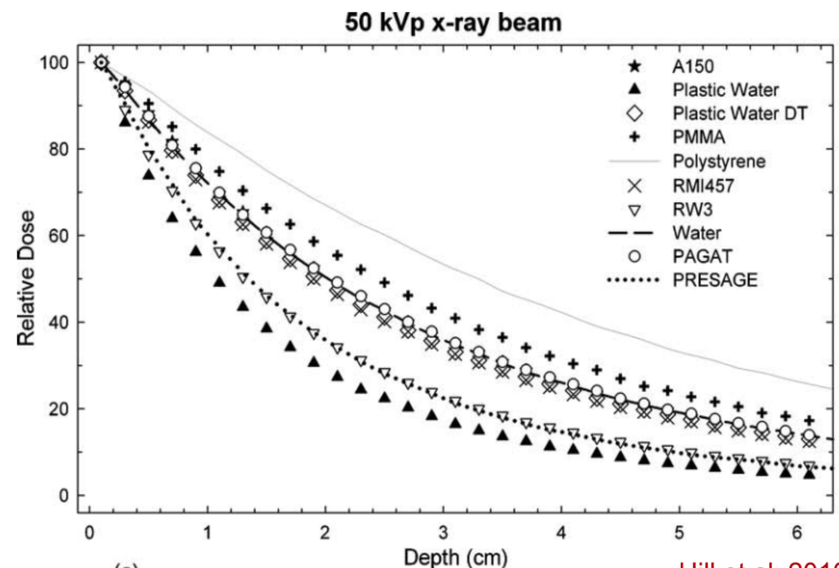
1. Virual Water, Med-Cal, Inc, Verona, WI
2. Standard Imaging, Middleton, WI

Captain’s Wheel



Setup advantages

- Captain's wheel:
  - Dose-rate conversion coefficient
  - Radial dose function
  - Azimuthal anisotropy
- Liquid water medium:
  - Avoids water-mimicking plastics
  - Avoids uncertainties associated with converting from dose-to-solid phantom to dose-to-liquid water[1]
  - Only water is between source and TLDs

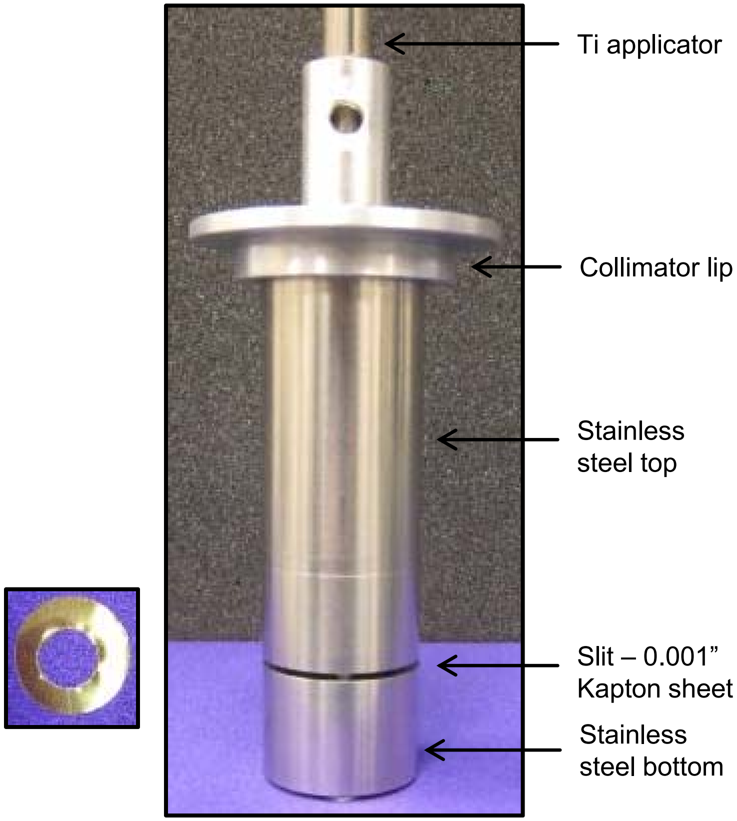


Hill et al. 2010

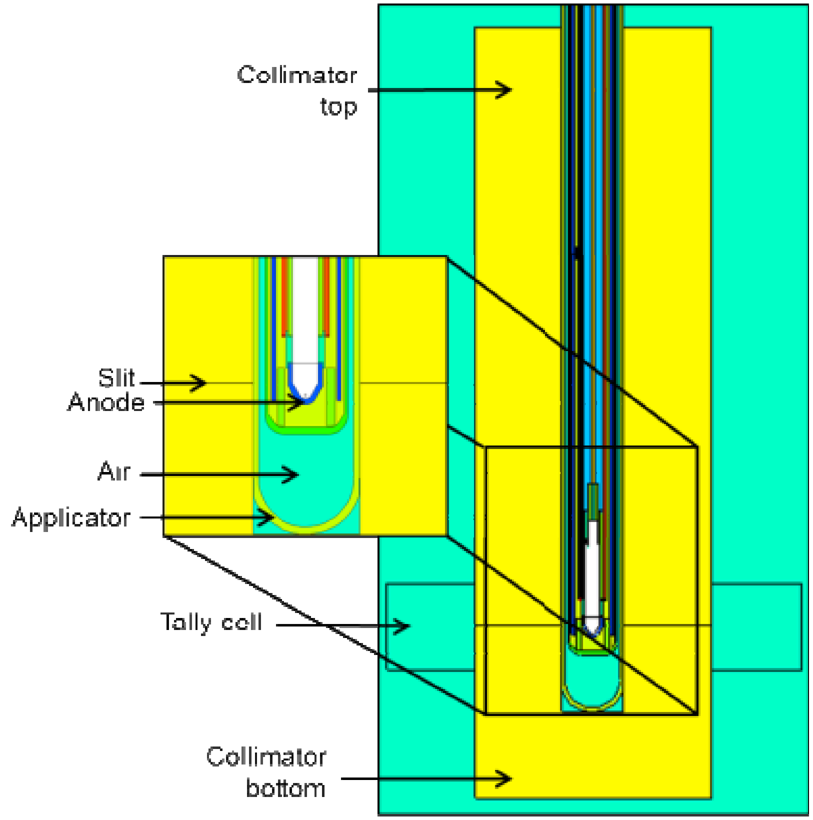
1. Hill et al., "The water equivalence of solid phantoms for low energy photon sources," Med. Phys. **37**, 4355-4363 (2010).

Stainless steel collimator

Stainless steel collimator

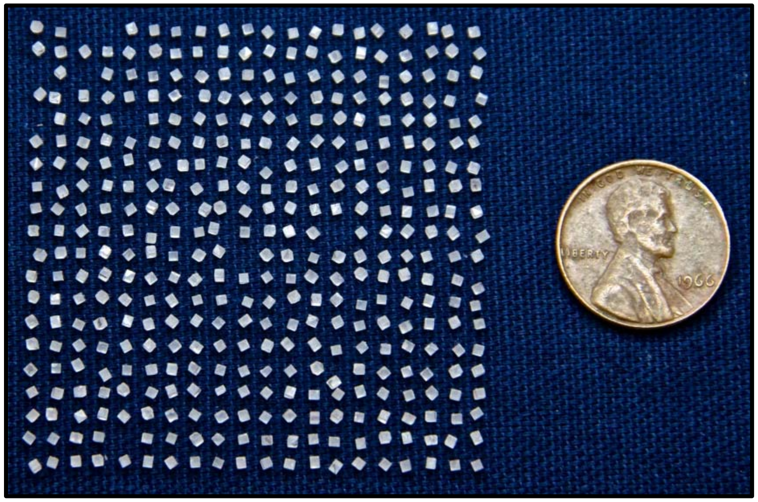


Visual editor rendering



TLD Correction Factors

- Introduction
- Methods
- Results
- Conclusions
- Future Work



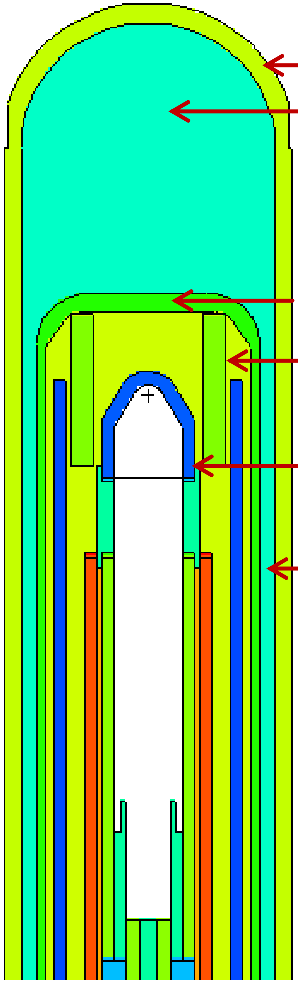
- TLD-100 LiF:Mg,Ti microcubes:
  - Sorted to a reproducibility of 2%
  - Handled according to the Cameron process
- Analysis:

$$\dot{D}(r,\theta) = \frac{R \cdot N \cdot \left(\frac{k_{bq(Axxent)}}{k_{bq(^{60}Co)}}\right)}{C(r) \cdot t}$$

- R — TLD reading in nC corrected for individual chip factors and background
- N — Calibration curve conversion from nC to cGy
- $\frac{k_{bq(Axxent)}}{k_{bq(^{60}Co)}}$ — Intrinsic energy dependence correction factor
- $C(r)$ — Phantom correction factor
- t — Total irradiation time

Monte Carlo simulations

- Version 5 of the Monte Carlo N-Particle code (MCNP5) was used to[1]:
  - Perform a computational dosimetric characterization
  - Determine measurement correction factors
- The source and applicator were modeled using material and dimension specifications provided by Xoft Inc.
  - Davis developed and verified the original bare source model[2]
- χ_{Ti}, $g_{Ti}(r,\theta)$, and $F_{Ti}(r,\theta)$: collision-kerma tally (F6)
- $C(r)$: energy deposition tally (*F8)

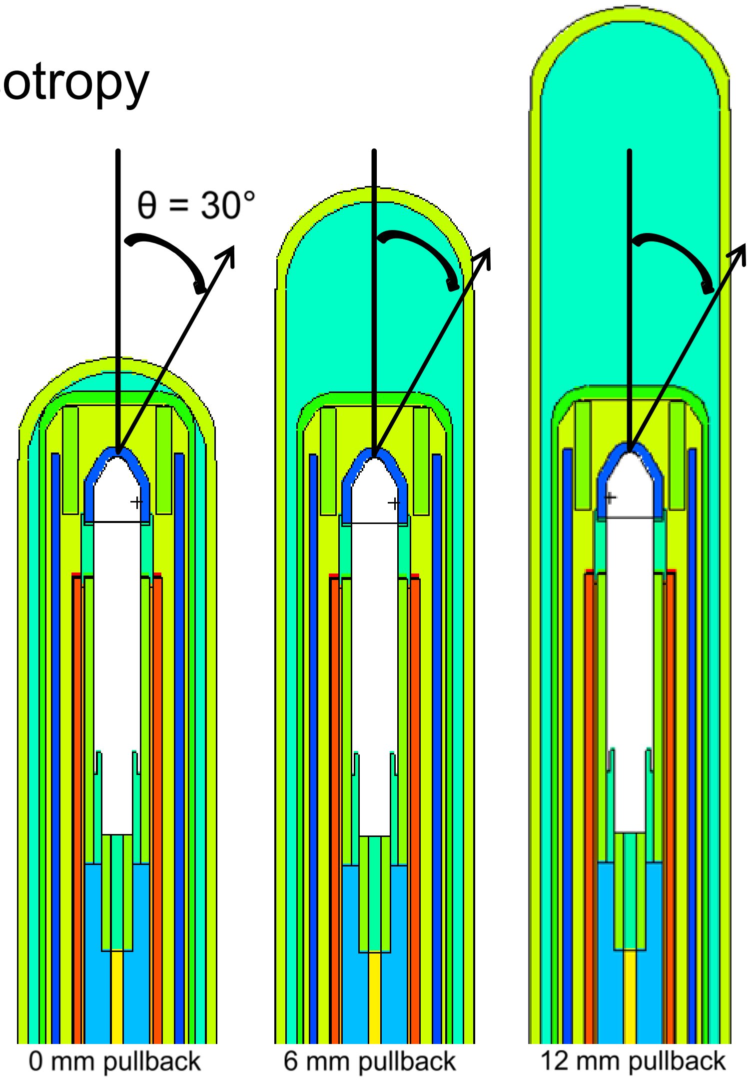


1. X-5 Monte Carlo Team (2005). MCNP – A General Monte Carlo N-Particle Transport Code, Version 5, Report LA-UR-03-1987. Los Alamos National Laboratory, Los Alamos, NM.

2. Davis, S. D. (2009). Air kerma strength determination of a miniature x-ray source for brachytherapy applications. Ph.D. dissertation, University of Wisconsin-Madison.

Cervical applicator implementation

- Dwell-position-dependent polar anisotropy
- Cervical applicator does not have a uniform thickness of titanium
  - Rounded dome is ~0.5 mm thick
  - Barrel ~0.4 mm thick
  - Anode geometry
  - Changing air gap distance
- Position of the source will impact the dose distribution surrounding the applicator
- Simulations: 0, 6, 12 mm pullback



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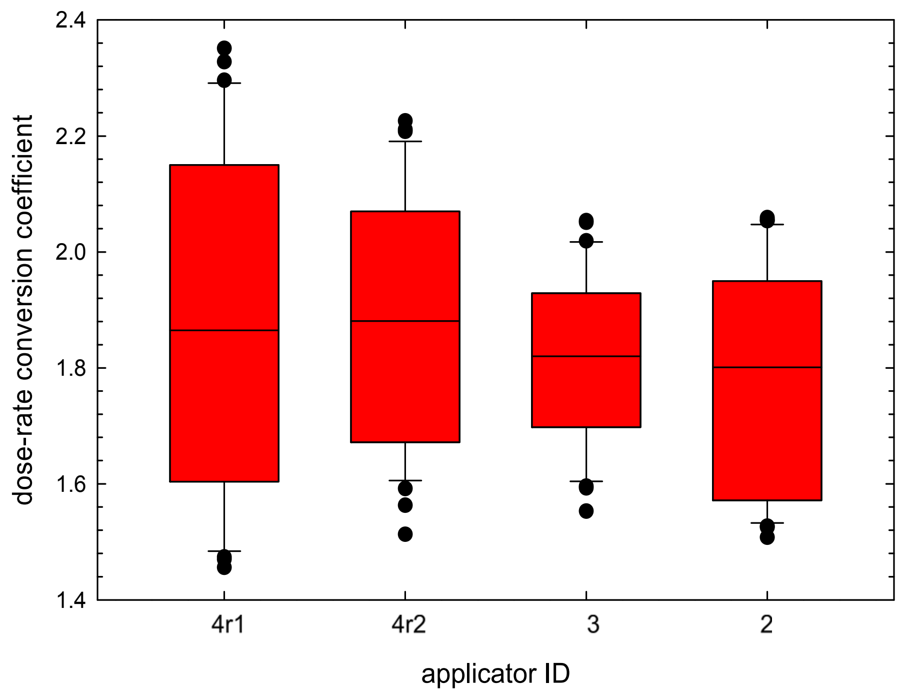
Dose-rate conversion coefficient

DRCC results



Analysis

- 3 applicators and 1 source
- Is one representative DRCC value acceptable for all applicators?
- 1-Way ANOVA analysis
- There is no statistically significant difference between the applicators
  - Azimuthal anisotropy

Azimuthal anisotropy

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Ti applicator going into page

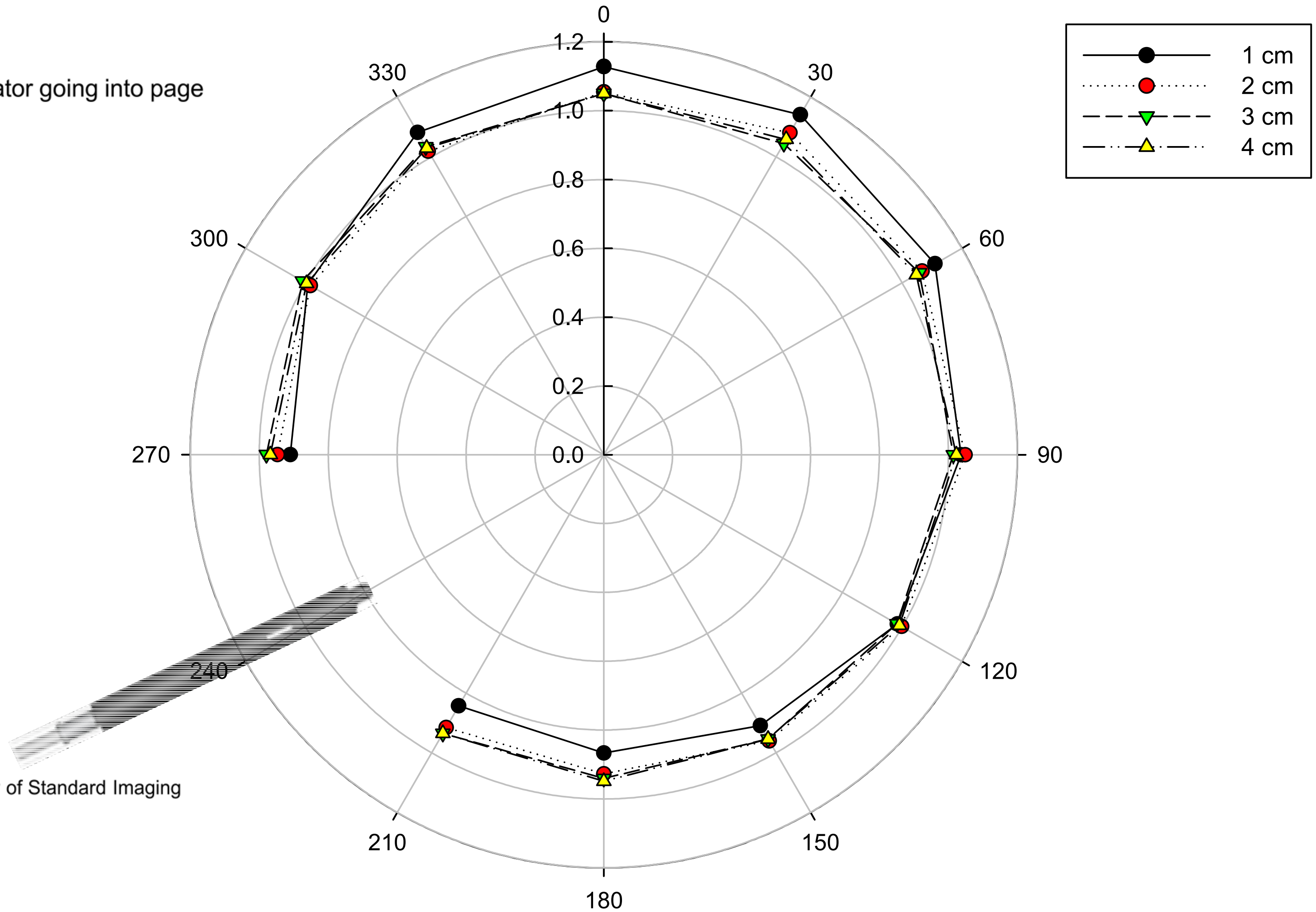
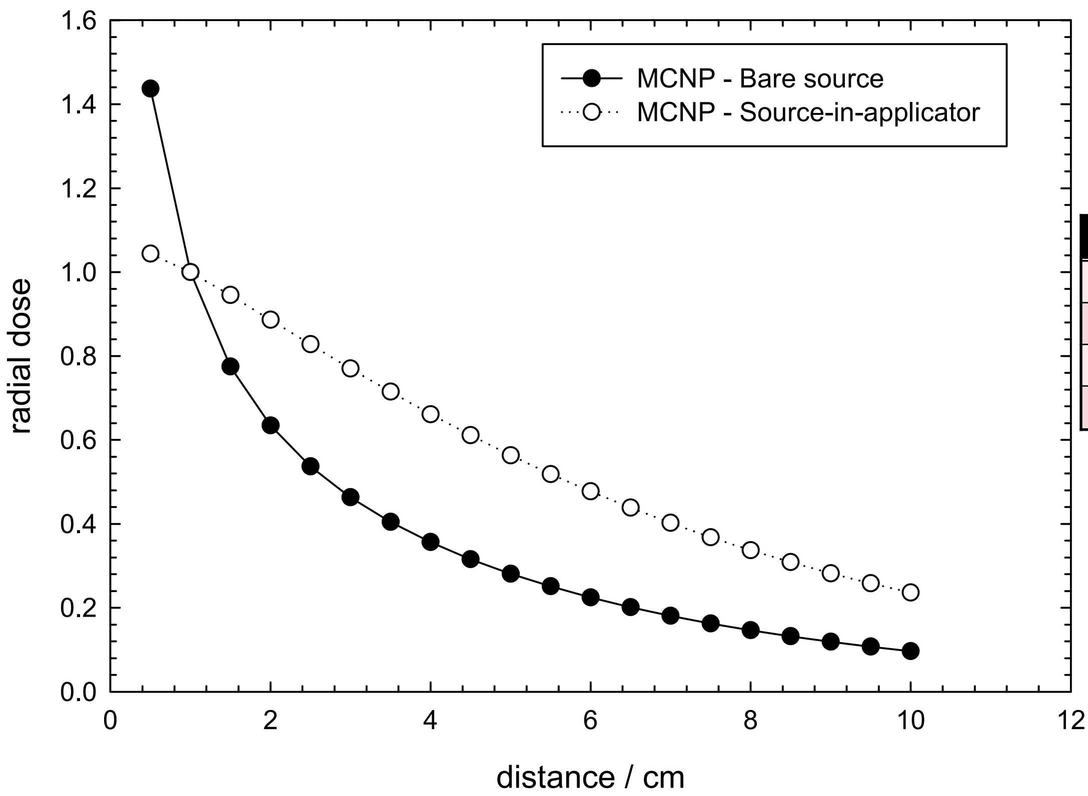


Image courtesy of Standard Imaging

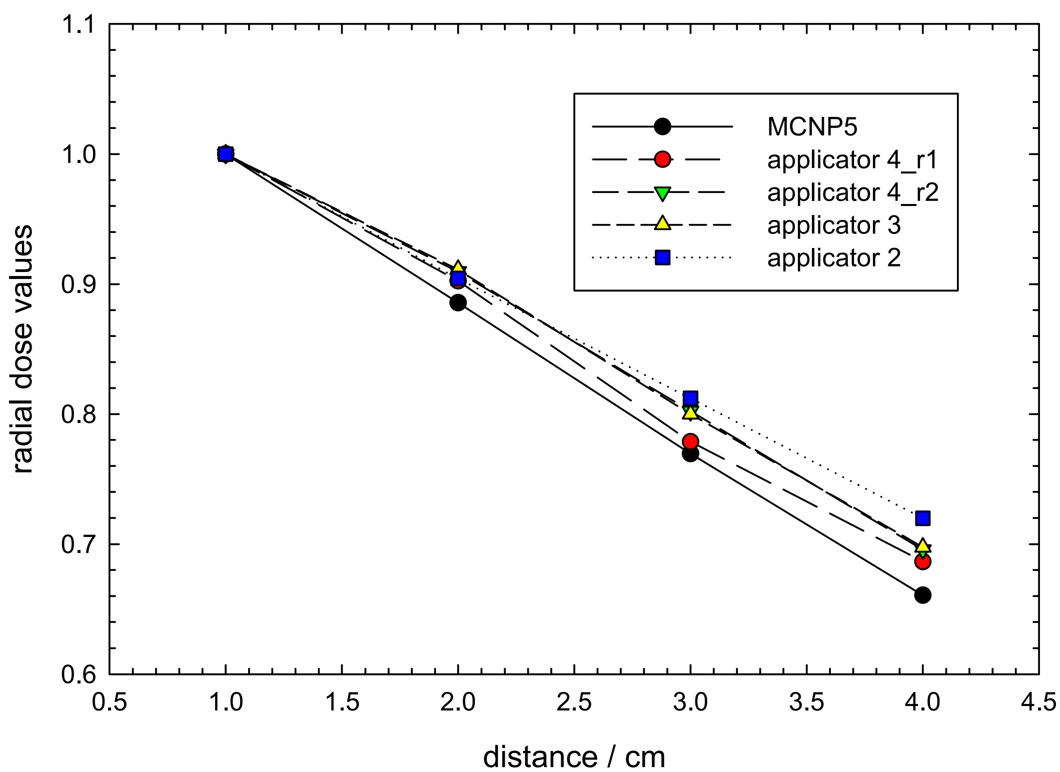
Radial dose function

- Introduction
- Methods
- Results
- Conclusions
- Future Work



distance /cm	MC bare source	MC 6 mm	% diff
1	1.000	1.000	0.00
2	0.634	0.886	-28.4
3	0.463	0.770	-39.9
4	0.356	0.661	-46.1

Radial dose function



- MCNP5 vs. TLD

Overall Average	RDF	MCNP	% difference
1	1.000	1.000	0.00
2	0.907	0.886	2.40
3	0.798	0.780	3.73
4	0.700	0.661	5.94

- Applicator comparison

distance / cm	min. value	max. value	max % difference
1	1.000	1.000	0.00
2	0.902	0.911	-0.96
3	0.779	0.812	-4.11
4	0.686	0.720	-4.62

- Uncertainty budget is being developed
- Expected uncertainty ~ 5% (k=1)

Polar Anisotropy

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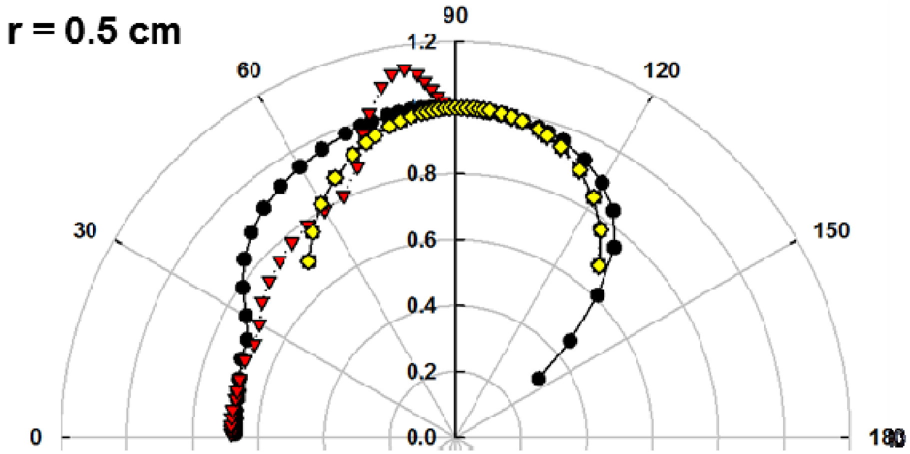

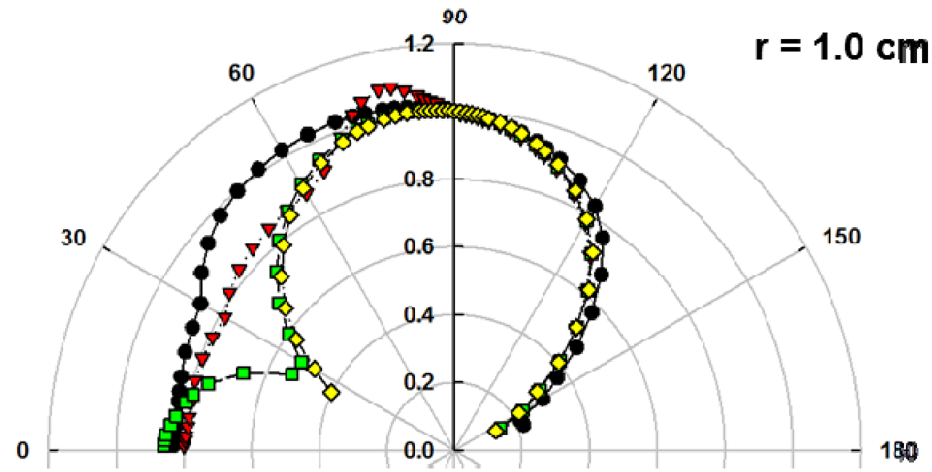

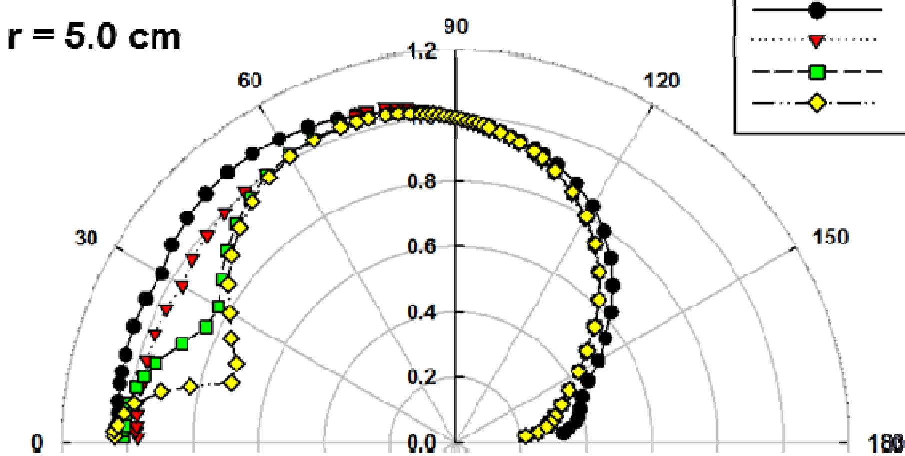

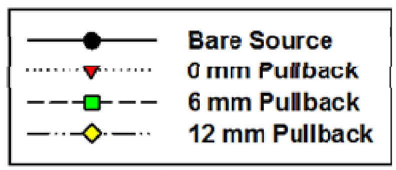

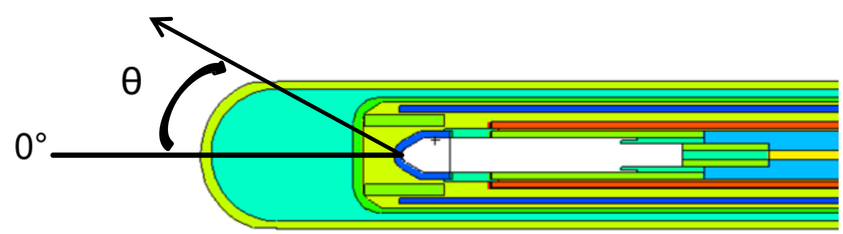

* All data processed with L_{eff} = 0.1 cm

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Conclusions

- NIST has established an air-kerma rate standard for the Xoft Axxent® source
  - Need for NIST traceability for other electronic brachytherapy sources
- Established a modified TG-43 dosimetry formalism
  - Implementation by Xoft (an iCAD company) is ongoing
  - Applied to other electronic brachytherapy sources
- A representative TG-43 dosimetry dataset is appropriate
- Multiple datasets can be utilized to accommodate the geometry of the applicator

Future work

- Repeat Captain's wheel measurements with multiple sources
- Polar anisotropy measurements
  - TLD and film
- Azimuthal anisotropy measurements
  - Contribution from source vs. applicator positioning
- Attix Free Air Chamber measurements

Acknowledgements

- Larry DeWerd, PhD
- Wesley Culberson, PhD
- John Micka

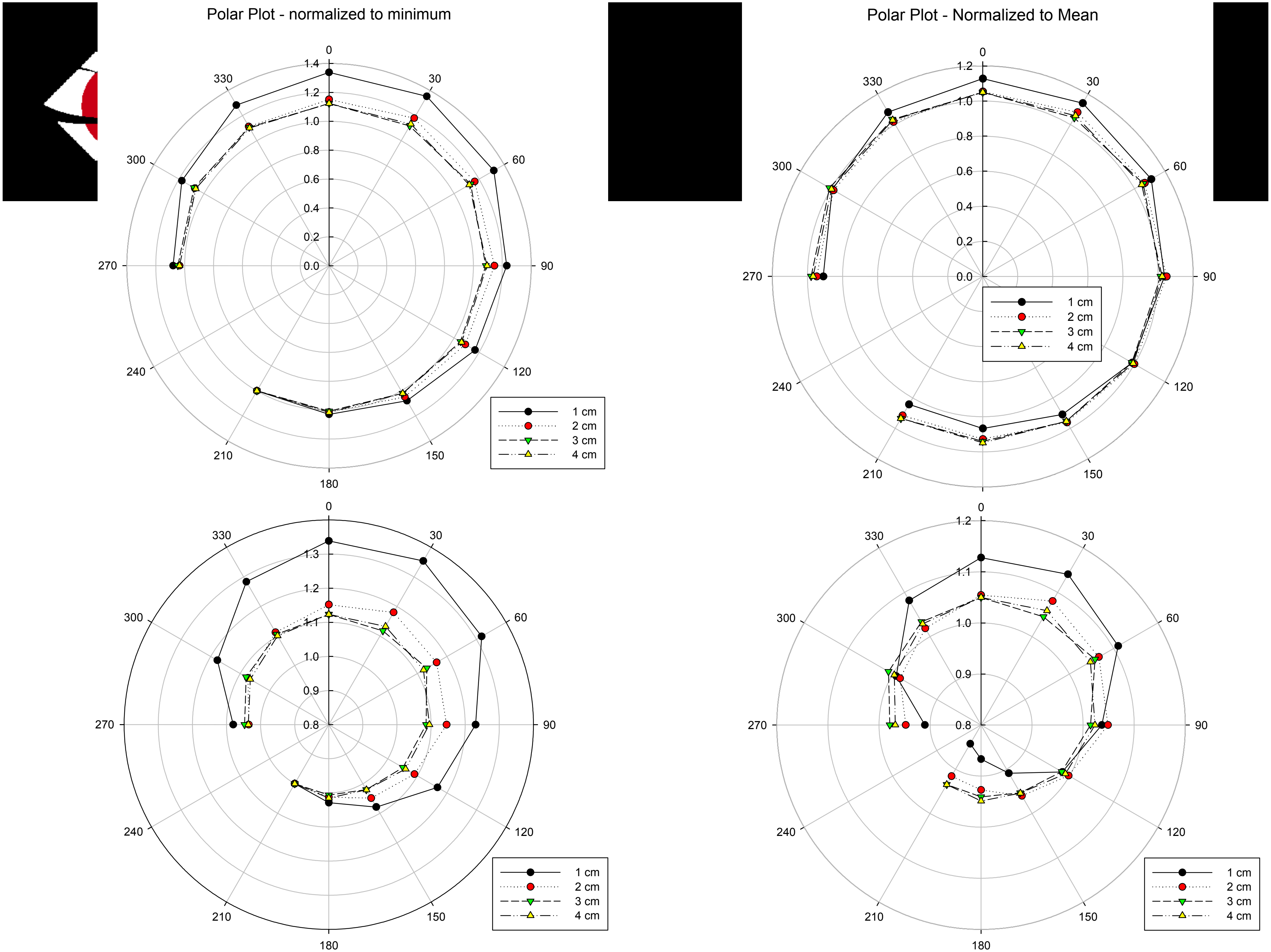
- UWMRRC staff and students

- UWADCL customers
- Xoft Inc. (a subsidiary of iCAD) for providing partial funding for this work
- NIH grant T32-CA009206

Questions?

DCF Uncertainty

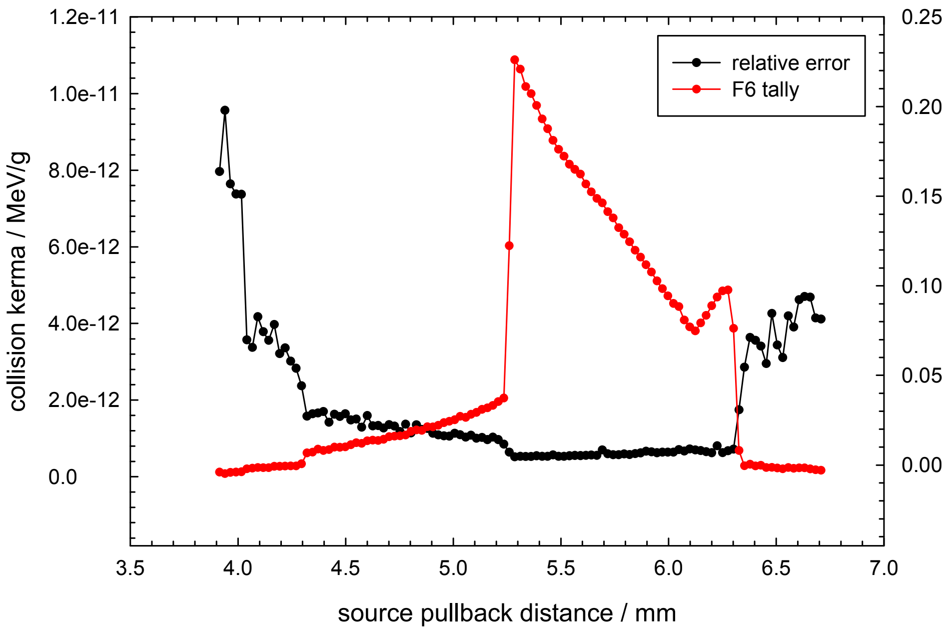
	Relative Standard Uncertainty (%)	
Parameter	Type A	Type B
R-corrected TLD reading		
TLD reproducibility	3.97	0
TLD positioning	0.42	0
TLD irradiation time	0.14	0
PMT linearity correction	0	0.1
Reader stability	0	0
N-calibration coefficient		
Calibration curve deviation	1.47	0
Air-kerma rate determination	0	0.8
TLD positioning	0	0.1
PMT linearity correction	0	0.1
Field uniformity	0	0
Reader stability	0	0.1
Air-kerma rate determination	1.52	0.5
Phantom correction (Axxent component)		
MC statistical uncertainty	0.05	0
Photon spectrum	0	0.21
Cross section	0	0.26
Phantom correction (Co^{60} component)		
MC statistical uncertainty	0.07	0
Photon spectrum	0	0.04
Cross section	0	0.01
Energy dependence correction		
Energy dependence determination	0.99	0.97
Energy dependence application	0	0.25
Combined uncertainty	4.63	1.34
Total uncertainty (k=1)	4.8	
Expanded uncertainty (k=2)	10	



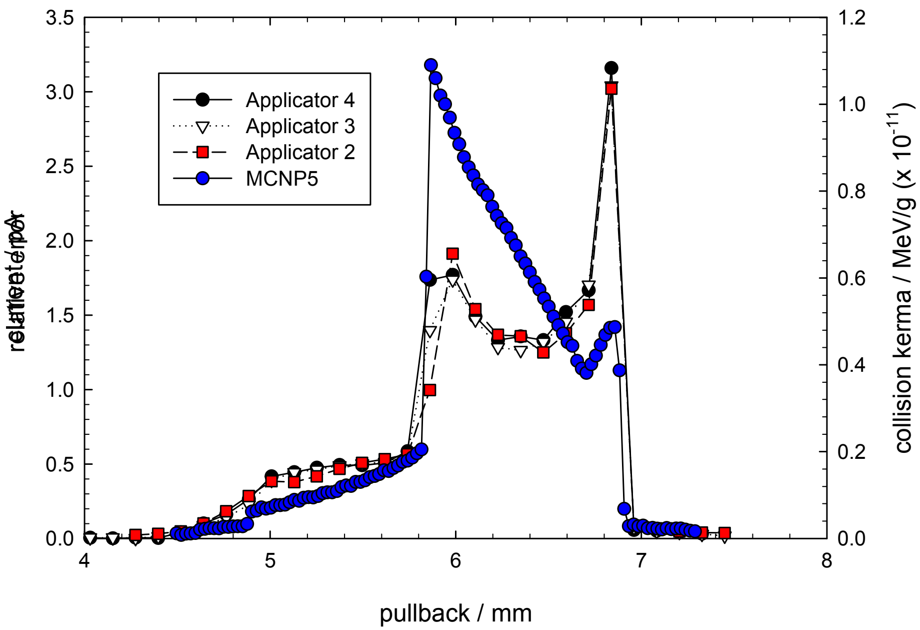
Polar Plot - normalized to minimum
Polar Plot - Normalized to Mean
0
30
60
90
120
150
180
210
240
270
300
330
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.8
0.9
1.1
1.3
1 cm
2 cm
3 cm
4 cm

Stainless steel collimator

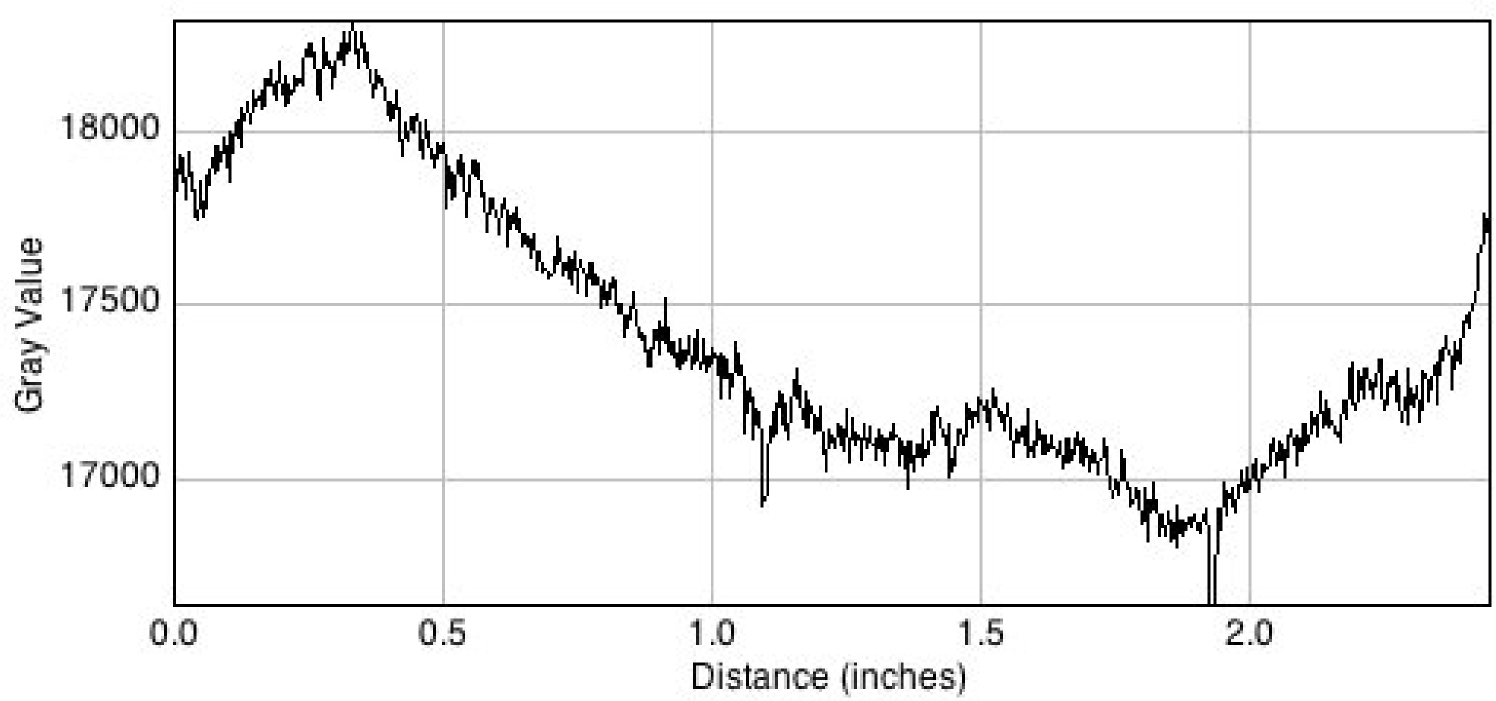
MCNP simulation results



Visual Editor rendering



This is without any flexing of the applicator. We know the applicator was centered in the acrylic.



Outline

- Introduction
  - Xoft source, cervical applicator
  - State challenges
    - NIST traceable
    - New formalism
    - Account for applicator (show MCNP and what happens if we don’t account for applicator)
    - Dwell position dependent polar anisotropy
    - Applicator-to-applicator variation
- Approach
  - MCNP
  - Attix FAC
  - Well chamber – NIST-traceable wc cal coefficient
  - TLD-100 microcubes
  - Anode output profiles
- Conclusions
- Future work
  - Additional source measurements
  - Attix FAC measurements

Treatment planning

- AAPM's TG-43[1] dosimetry protocol
  - Homogeneous patient geometry
  - Ignores the presence of any applicators
  - Calculated dose overestimates the actual dose received by the patient
- Need to quantify the effect of the applicator
- Need to develop a representative set of parameters that accounts for the presence of the applicator
  - Applicator-to-applicator variation
- Applicator geometry introduces dwell-position-dependent polar anisotropy

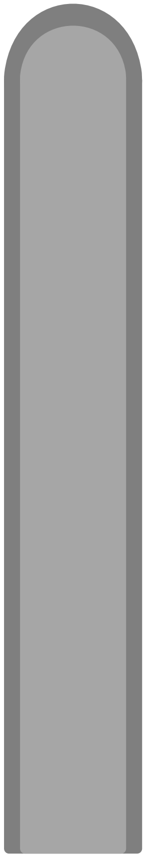
1. Rivard, M. J., Coursey, B. M., DeWerd, L. A., Hanson, W. F., Huq, M. S., Ibbott, G. S., Mitch, M. G., Nath, R., and Williamson, J. F. (2004). Update of AAPM Task Group No. 43 report: A revised AAPM protocol for brachytherapy dose calcualtions. Med. Phys., 31:633-674.

Treatment planning

- AAPM's TG-43[1] dosimetry protocol
  - Homogeneous patient geometry
  - Ignores the presence of any applicators
  - Calculated dose overestimates the actual dose received by the patient
- Patient impact
  - Under dosing of the patient
  - Inaccurate calculations of dose to OAR
- Need to quantify the effect of the applicator
- Need to develop a representative set of parameters that accounts for the presence of the applicator

1. Rivard, M. J., Coursey, B. M., DeWerd, L. A., Hanson, W. F., Huq, M. S., Ibbott, G. S., Mitch, M. G., Nath, R., and Williamson, J. F. (2004). Update of AAPM Task Group No. 43 report: A revised AAPM protocol for brachytherapy dose calcualtions. Med. Phys., 31:633-674.

Source pullback location



UW Attix Free Air Chamber

- Primary air kerma measurement comparable to NIST
  - Measure up to 50 kV x-rays
- Measured air-kerma rate of the source at 50 cm
  - Azimuthal anisotropy accounted for by measuring at each of the cardinal angles
- Standard Imaging[1] SuperMAX™ electrometer was used to measure the charge and current

UW Attix Free Air Chamber

1. Standard Imaging, Middleton, WI