Monte Carlo Dose Calculations: Backbone of NextGEN Brachytherapy

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Acknowledgements

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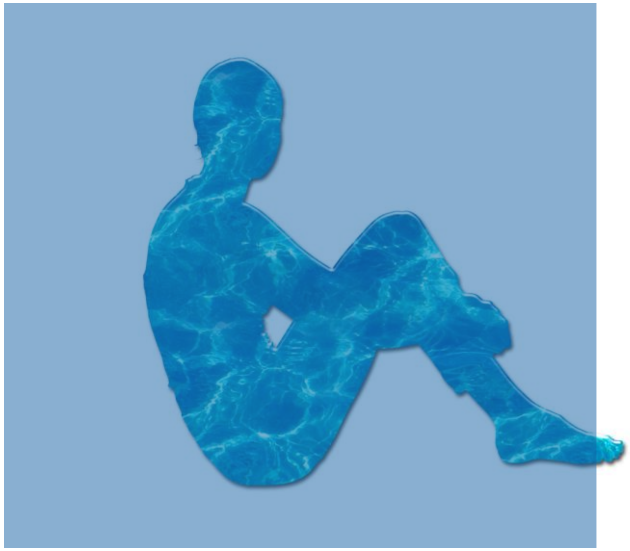
NextGEN Brachytherapy?

- Do what we are currently doing but better…
  - Clinical adoption of better dose calc. algo.

- Potentially do differently
  - New applicators
  - New sources
  - New brachytherapy procedures / sites

Never again



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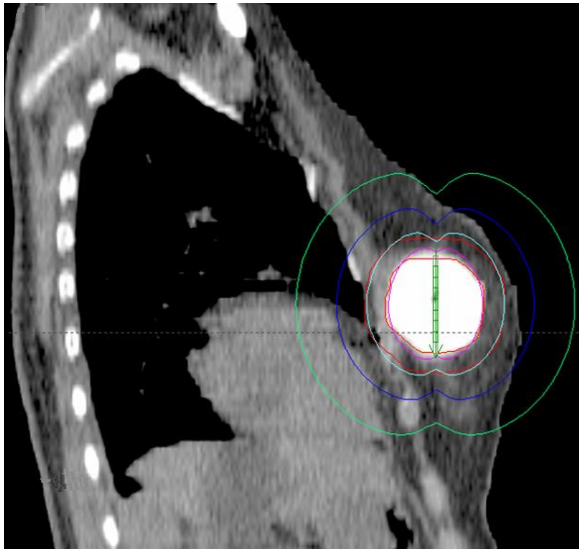
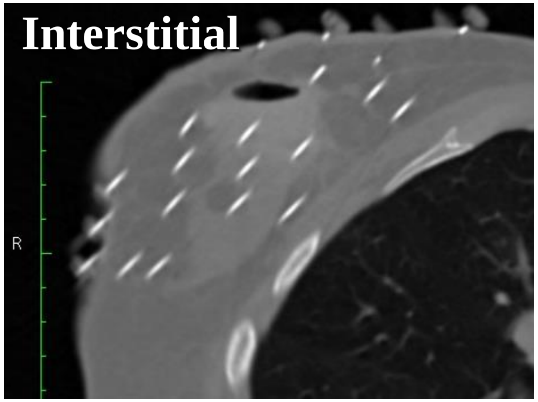
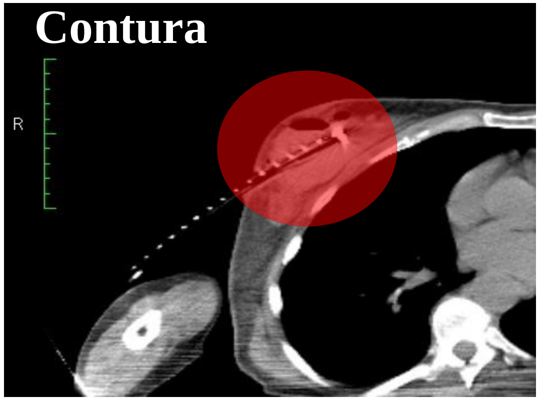
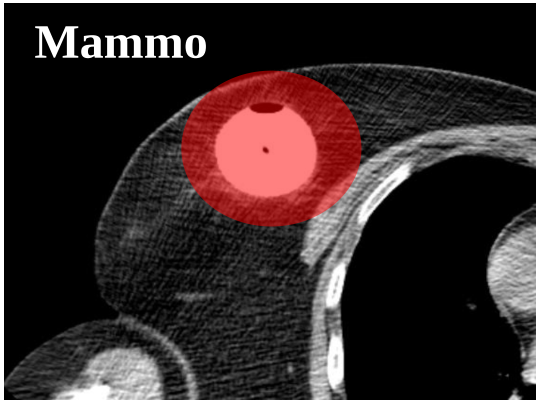
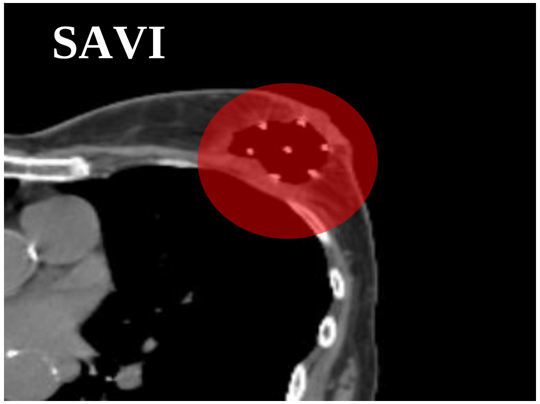


Patient and technique dependent!



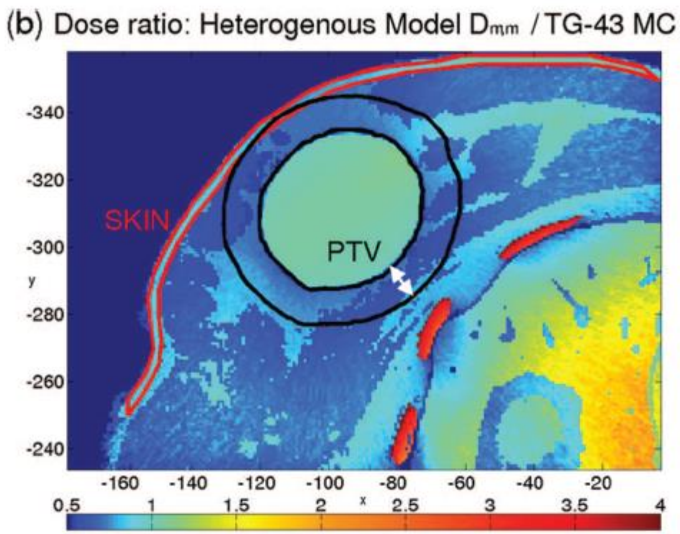






Low Energy Breast Brachytherapy:

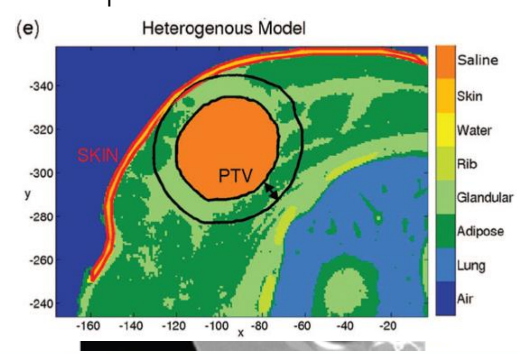
Seed/**Xoft** (…and IntraBeam, …)



TG-186< TG-43 TG-186> TG-43

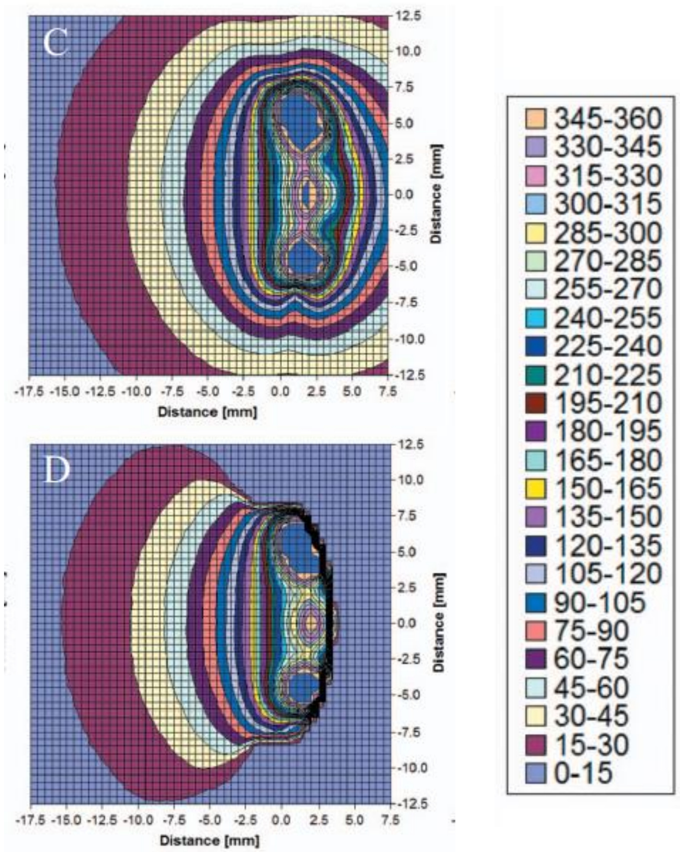
DVH	% differences range
D_{90}	-36% to -33%
V_{100}	- 54% to – 29%
V_{200}	- 97% to - 25%
$D_{0.2cc}$ (Skin)	- 19% to 0%

- Large DVH decreases in $D_{m,m}$ compared to TG-43
- Higher calculated rib dose

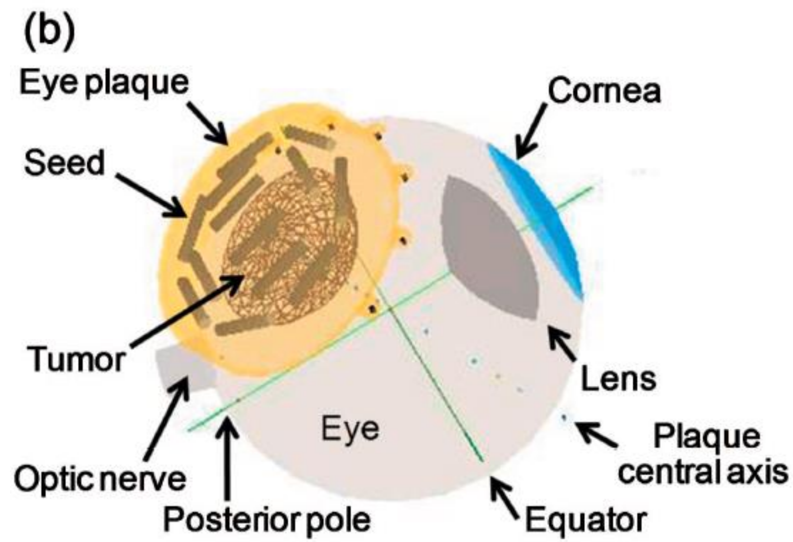


White *et al* : Med. Phys. 2014

Eye Plaque

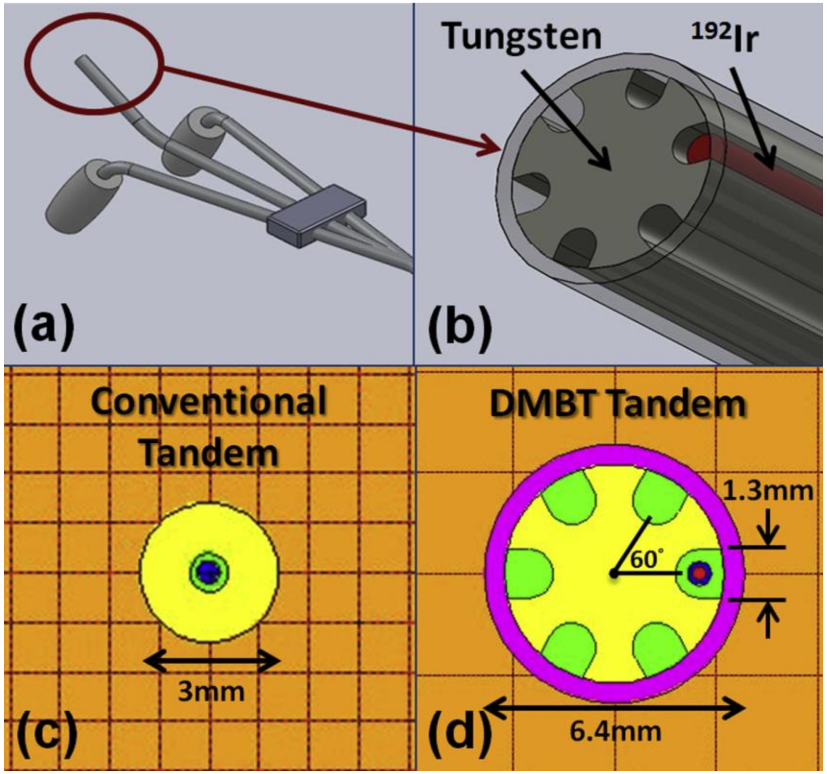


Melhus and Rivard, Med Phys 35 (2008)

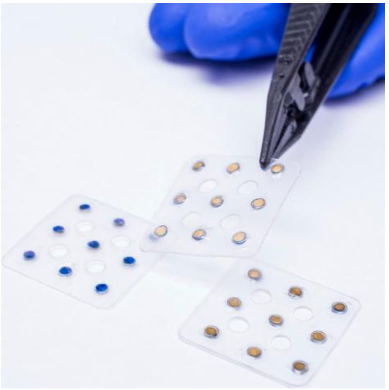


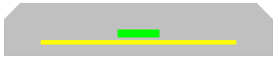
Rivard et al, Med Phys 38 (2011) : 20-30% point of interests in the eye; up to 90% decrease off axis

Extreme BT Shielding: HDR ^{192}Ir & ^{103}Pd



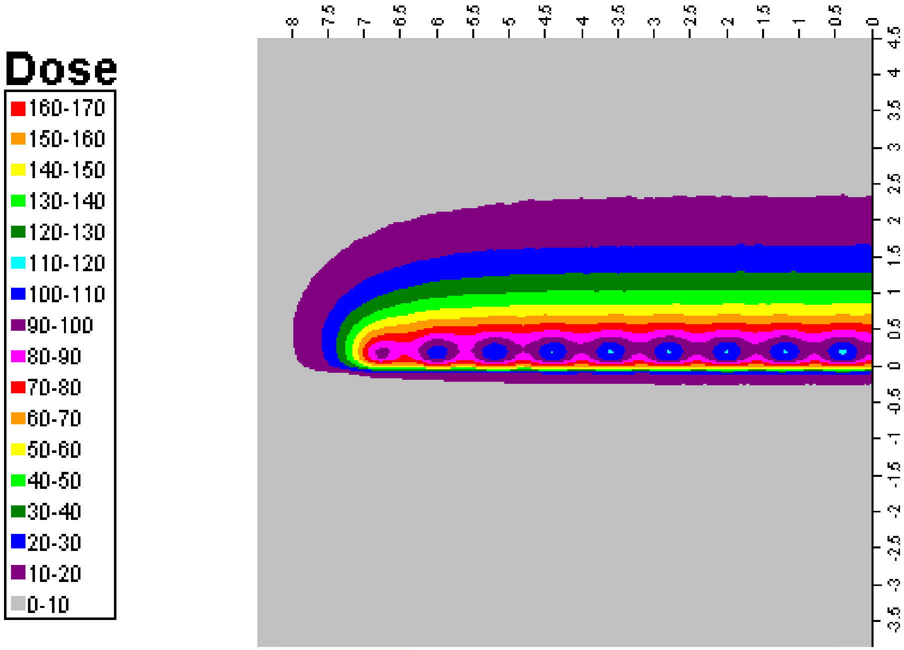
Han et al, *IJROBP* 89, 666-673 (2014)





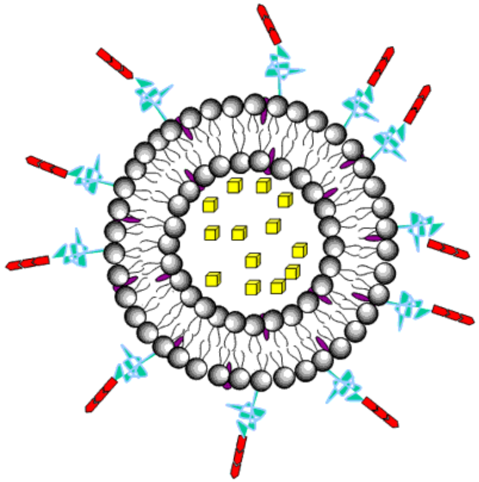
2.5 mm diam.

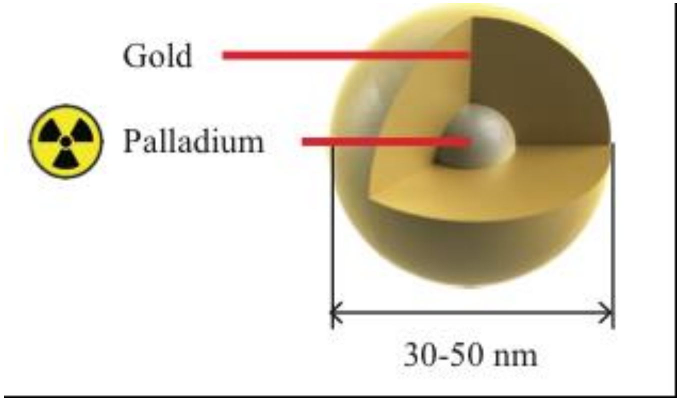
CivaSheet

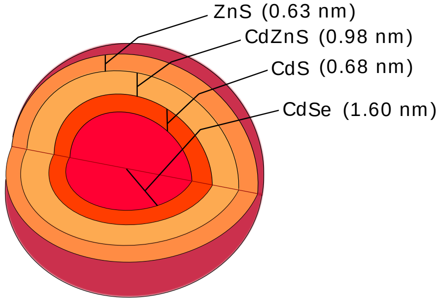


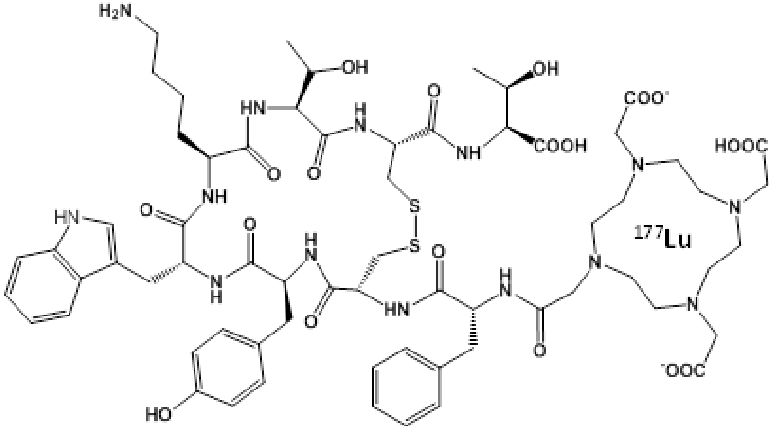
From MJ Rivard, Work in Progress

Targeted Therapy / Theragnostic









Sensitivity of Anatomic Sites to Dosimetric Limitations of Current Planning Systems

anatomic site	photon energy	absorbed dose	attenuation	shielding	scattering	beta/kerma dose
prostate	high					
	low	XXX	XXX	XXX		
breast	high				XXX	
	low	XXX	XXX	XXX		
GYN	high			XXX		
	low	XXX	XXX			
skin	high			XXX	XXX	
	low	XXX		XXX	XXX	
lung	high				XXX	XXX
	low	XXX	XXX		XXX	
penis	high				XXX	
	low	XXX			XXX	
eye	high			XXX	XXX	XXX
	low	XXX	XXX	XXX	XXX	

Rivard, Venselaar, Beaulieu, *Med Phys* 36, 2136-2153 (2009)

Enabling clinical use of advanced dose calculation algorithms

Report of the Task Group 186 on model-based dose calculation methods in brachytherapy beyond the TG-43 formalism: Current status and recommendations for clinical implementation

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The charge of Task Group 186 (TG-186) is to provide guidance for early adopters of model-based dose calculation algorithms (MBDCAs) for brachytherapy (BT) dose calculations to ensure practice uniformity. Contrary to external beam radiotherapy, heterogeneity correction algorithms have only recently been made available to the BT community. Yet, BT dose calculation accuracy is highly dependent on scatter conditions and photoelectric effect cross-sections relative to water. In specific situations, differences between the current water-based BT dose calculation formalism (TG-43) and MBDCAs can lead to differences in calculated doses exceeding a factor of 10. MBDCAs raise three major issues that are not addressed by current guidance documents: (1) MBDCA calculated doses are sensitive to the dose specification medium, resulting in energy-dependent differences between dose calculated to water in a homogeneous water geometry (TG-43), dose calculated to the local medium in the heterogeneous medium, and the intermediate scenario of dose calculated to a small volume of water in the heterogeneous medium. (2) MBDCA doses are sensitive to voxel-by-voxel interaction cross sections. Neither conventional single-energy CT nor ICRU/ICRP tissue composition compilations provide useful guidance for the task of assigning interaction cross sections to each voxel. (3) Since each patient-source-applicator combination is unique, having reference data for each possible combination to benchmark MBDCAs is an impractical strategy. Hence, a new commissioning process is required. TG-186 addresses in detail the above issues through the literature review

 0094-2405/2012/39(10)/6208/29/$30.00

Report of the Task Group 186 on model-based dose calculation methods in brachytherapy beyond the TG-43 formalism: Current status and recommendations for clinical implementation

1. recommendations to MBDCA early-adopters to evaluate:
   - phantom size effect
   - inter-seed attenuation
   - material heterogeneities within the body
   - interface and shielded applicators
2. commissioning process to maintain inter-institutional consistency
3. patient-related input data
4. research is needed on:
   - tissue composition standards
   - segmentation methods
   - CT artifact removal

Approved by
ESTRO (BRAPHYQS, EIR)
AAPM (BTSC, TPC)
ABS (U.S. Phys Cmte)
ABG (Australia)

Specific commissioning process

- MBDCA specific tasks

  “Currently, only careful comparison to Monte Carlo with or w/o experimental measurements can fully test the advanced features of these codes”.

  - This is not sustainable for the clinical physicists.

You cannot beat the house!

DeWerd et al, AAPM/ESTRO TG138

TABLE IV. Propagation of best practice uncertainties (k=1 unless stated otherwise) associated with the transfer of air-kerma strength from a traceable NIST coefficient from the ADCL to the clinic for HDR high-energy brachytherapy sources.

Row	Measurement description	Quantity (units)	Relative propagated uncertainty (%)
1	A		
2	ADCL wel		
3	ADCL calibratio		
4	ADCL calibrati		
5	Clinic measur		
	Expand		

TABLE V. Propagation of best practice uncertainties (k=1 unless stated otherwise) in dose at 1 cm on the transverse plane associated with source-strength measurements at the clinic, brachytherapy dose measurements or simulation estimates, and treatment planning system dataset interpolation for low-energy (*low-E*) and high-energy (*high-E*) brachytherapy sources as relating to values presented in Fig. 1.

Row	Uncertainty component	Relative propagated uncertainty (%)	
		low-E	*high-E*
1	S_K measurements from row 5 of Tables I and IV	1.3	1.5
2	Measured dose	3.6	3.0
3	Monte Carlo dose estimate	1.7	1.6
4	TPS interpolation uncertainties	3.8	2.6
5	Total dose calculation uncertainty	4.4	3.4
	Expanded uncertainty (k=2)	8.7	6.8

Specific commissioning process

- MBDCA specific tasks

  “Currently, **only careful comparison to Monte Carlo** with or w/o experimental measurements can fully test the advanced features of these codes”.

  - This is not sustainable for the clinical physicists.

→ Led to a concerted international effort

Vision 20/20 Paper: 2010

TABLE I. Status of MBDCAs that can account for radiation scatter conditions and/or material heterogeneities and were useable in brachytherapy treatment planning systems as of 12 May 2010.

MBDCA system	Sponsor(s)	Radiation type	Clinical use	FDA/CE mark status	Release date
PLAQUE SIMULATOR	Astrahan	^{125}I+^{103}Pd photons	Y	N	1990
Collapsed cone	Ahnesjö, Russell, and Carlsson	^{192}Ir photons	N	N	1996
BRACHYDOSE	Yegin, Taylor, and Rogers	0.01–10 MeV photons	N	N	2004
MCPI	Chibani and Williamson	^{125}I+^{103}Pd photons	N	N	2005
GEANT4/DICOM-RT	Carrier *et al.*	Any	N	N	2007
Scatter correction	Poon and Verhaegen	^{192}Ir photons	N	N	2008
Hybrid TG-43:MC	Price and Mourtada, and Rivard *et al.*	Any	Y	Y	2009
ACUROS	Transpire/Varian	^{192}Ir photons	Y	Y	2009

V. NEEDED INFRASTRUCTURE

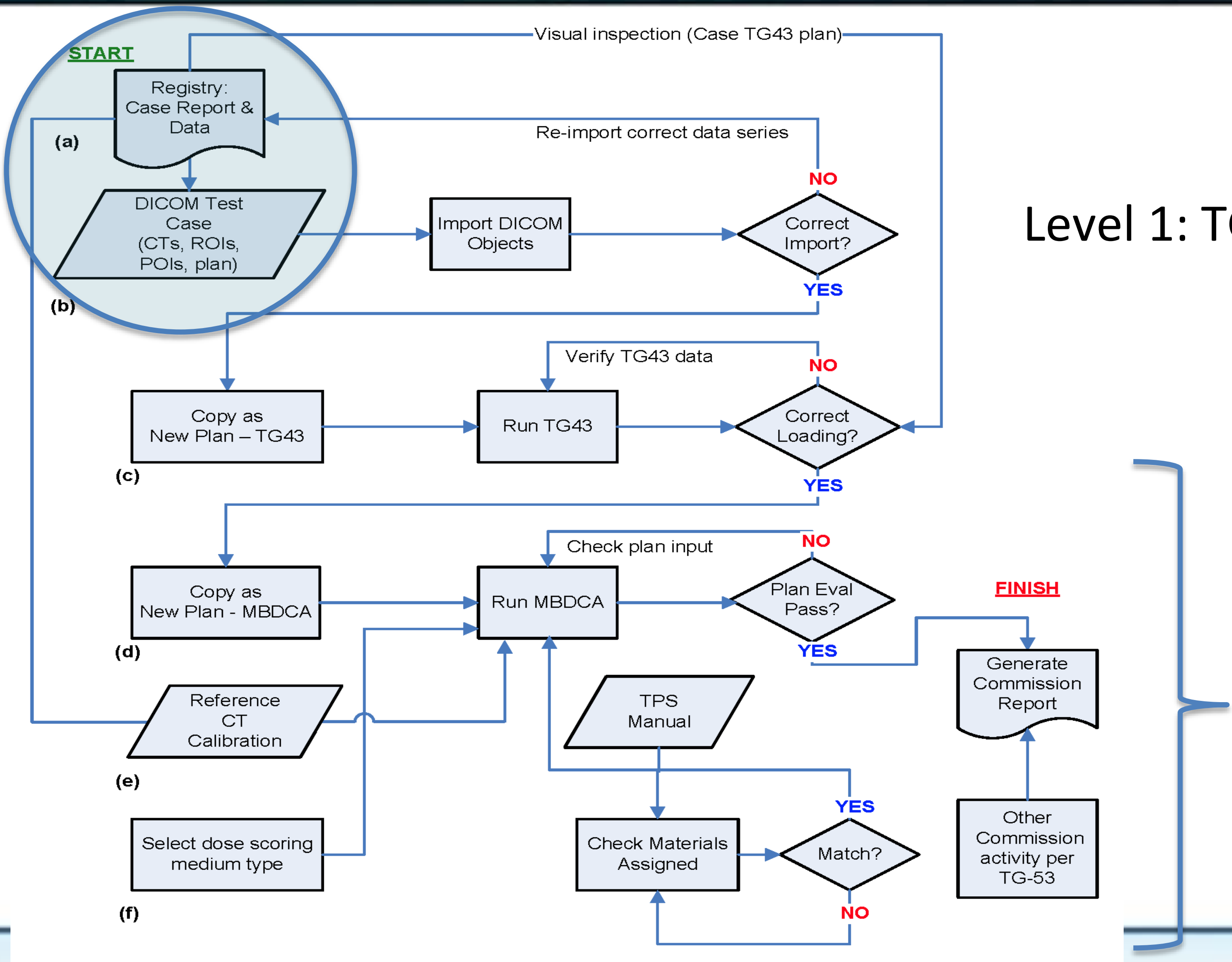
While MBDCAs are expected to produce more accurate dosimetric results than the current TG-43 formalism, the authors feel that the medical community should not immediately replace the current approach without careful consideration for widespread integration. Assessment of the current infrastructure is needed before assigning new resources, with opportunity for further cooperation of national and international professional societies.

V.A. Centralized dataset management

Societal recommendations and reference data do the clinical physicist no good if they cannot be readily implemented. Having quantitative data available beyond the scientific, peer-reviewed literature may be accomplished through expansion of the joint AAPM/RPC Brachytherapy Source Registry. An independent repository such as the Registry to house the reference data would facilitate this process–especially with international accessibility.

Rivard, Beaulieu, Mourtada, *Med. Phys.* 37, 2645-2658 (2010)

TG186 Commissioning Proposal



Level 1: TG43 like calc.

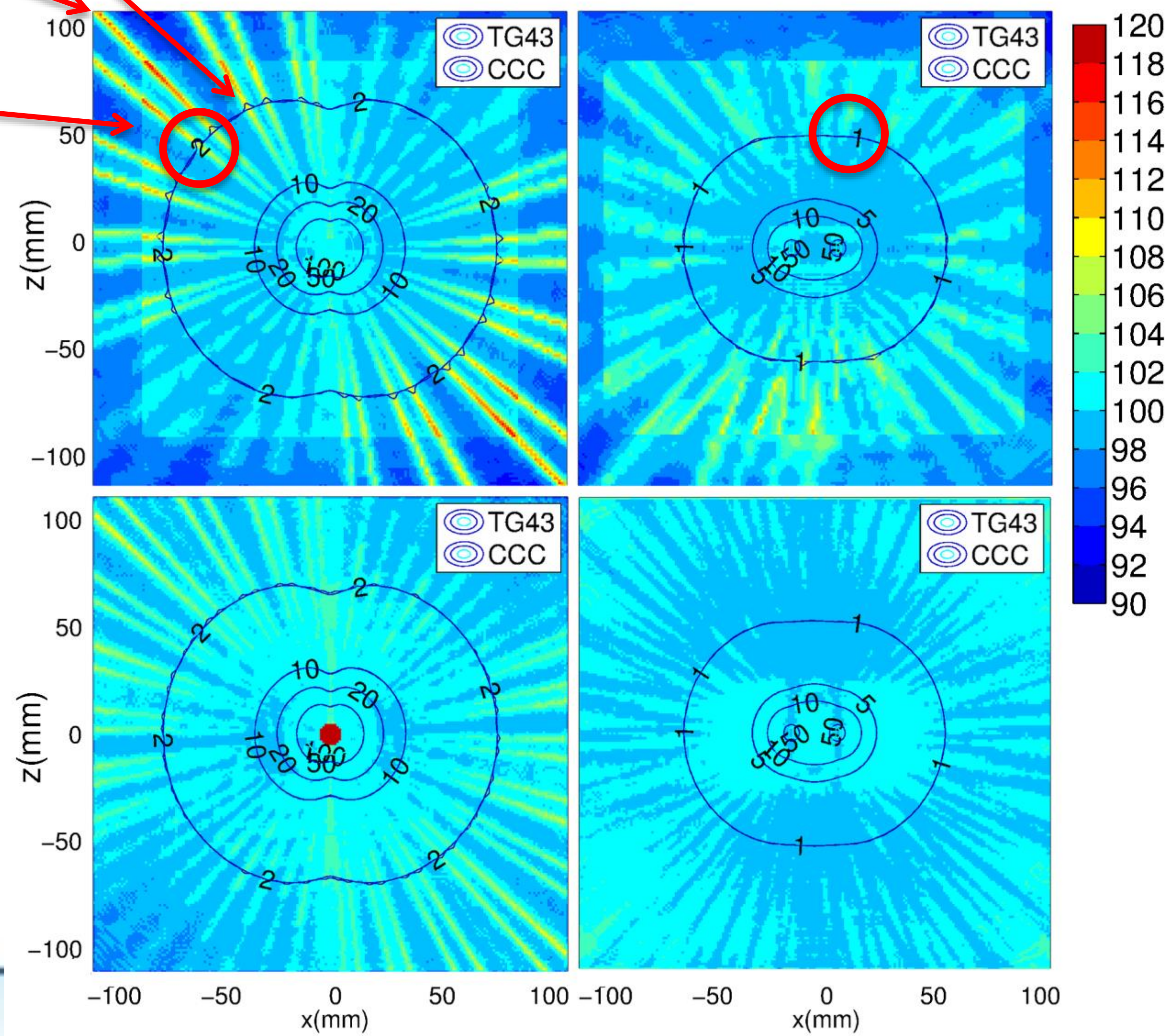
Level 2: Advanced dose calc.

ACE vs TG43: TG-43 conditions (L1)

1 dwell position **8 dwell positions**

STD (320/180)

Super High (1620/180)



Ma *et al*. Brachytherapy 2015;14:939–52

Joint AAPM/IROC Houston Registry of Brachytherapy Sources Meeting the AAPM Dosimetric Prerequisites

LDR ^{125}I Sources

Manufacturer	Sources	Model
BEBIG GmbH	IsoSeed I-125	I25.S17 plus
Best Medical International Inc	Best I-125 Source	2301
BARD Medical	^{125}Implant Seeds	STM1251
IsoAid, LLC	Advantage I-125	IAI-125A
Nucletron	selectSeed I-125	130.002
Theragenics	I-Seed I-125	AgX100

LDR ^{103}Pd Sources

Manufacturer	Sources	Model
Best Medical International Inc	Best Palladium - 103	2335
IsoAid, LLC	Advantage Pd-103	IAPd-103A
Theragenics Corporation	TheraSeed	200
CivaTech Oncology	CivaString	CS10

LDR ^{131}Cs Sources

Manufacturer	Sources	Model
IsoRay Medical Inc.	Proxcelan	CS-1 Rev2

PDR ^{192}Ir Sources

Manufacturer	Sources	Model
Nucletron, an Elekta company	Nucletron	mPDR-v1 (classic)
Varian Medical Systems, Inc. USA	GammaMed	PDR 12i
Varian Medical Systems, Inc. USA	GammaMed	PDR plus
Eckert & Ziegler BEBIG GmbH	BEBIG PDR	Ir2.A85-1

HDR ^{192}Ir Sources

Manufacturer	Sources	Model
Nucletron, an Elekta company	Nucletron mHDR	mHDR-v2
Nucletron, an Elekta company	Nucletron mHDR	mHDR-v1 ("Classic")
Varian Medical Systems, Inc.	Varian HDR	VS2000

Model-Based Dose Calculations

Reference dataset (DICOM archive) generated with MC simulation. Users may import these archives into TPS for benchmarking.

- Reference Data

TPS-specific seed DICOM archive. Users may start TPS calculation simply by importing these archives. CT images, RP and RS files are contained.

- Elekta Database
- Varian Database

Google web forum for sharing user ideas and experience.

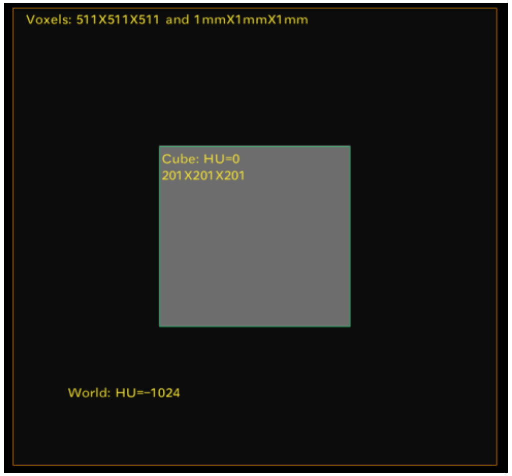
- MBDCA-BT Forum

Disclaimer for source-model definition files.

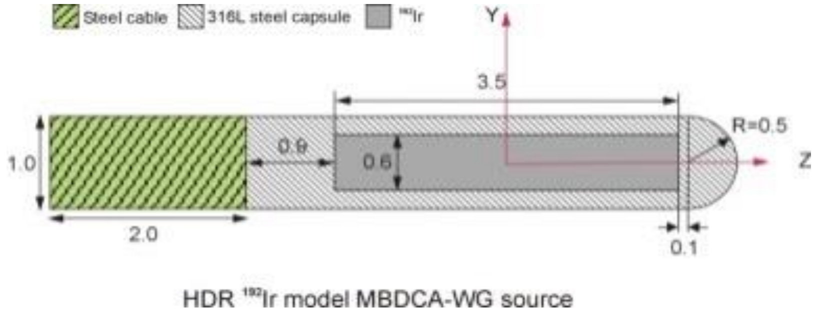
- Disclaimer

Test cases (tools)

DICOM (512 mm)^3
(1 mm)^3 voxel



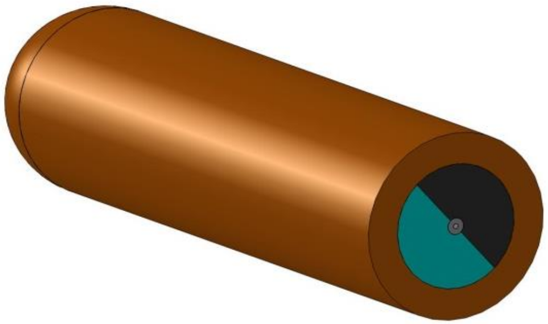
Generic HDR
^{192}Ir source



Ballester *et al.*, *Med. Phys.* 42, 3048-3062 (2015)

Shielded GYN applicator

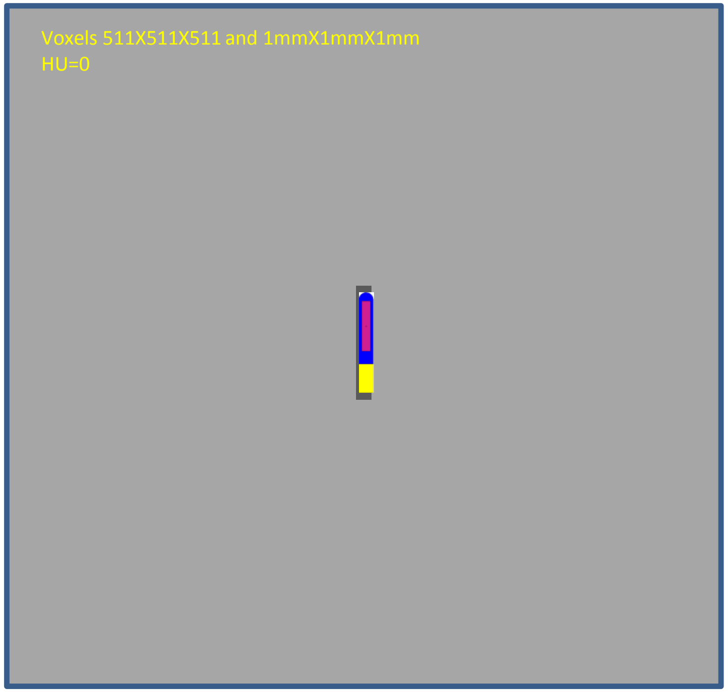
	Material	Elemental composition	Mass Density (g/cm^3)
Body	PMMA	$C_5O_2H_8$	1.19
Shield	Densimet D176	Fe (2.5%), Ni (5%), W (92.5%)	17.6



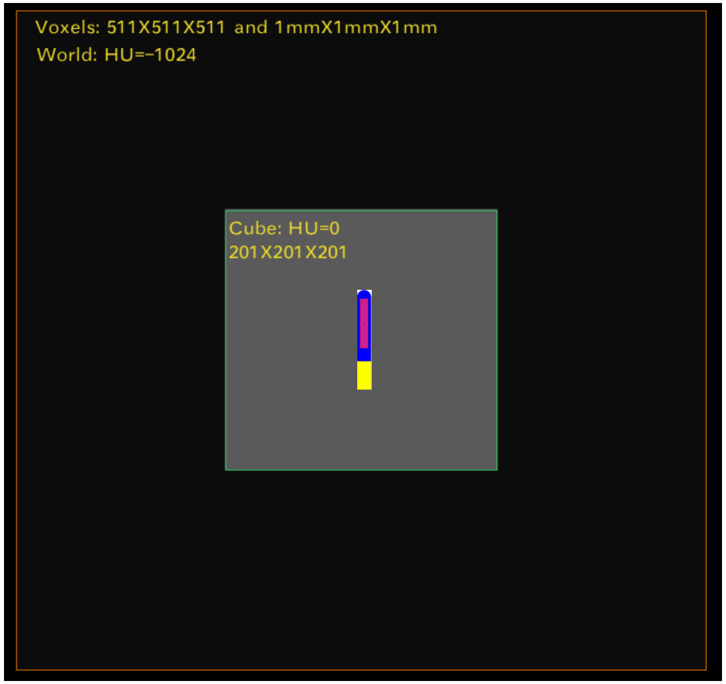
Ma, Vijande et al. Med Phys 2017 (In Press)

Test cases

- Test case 1



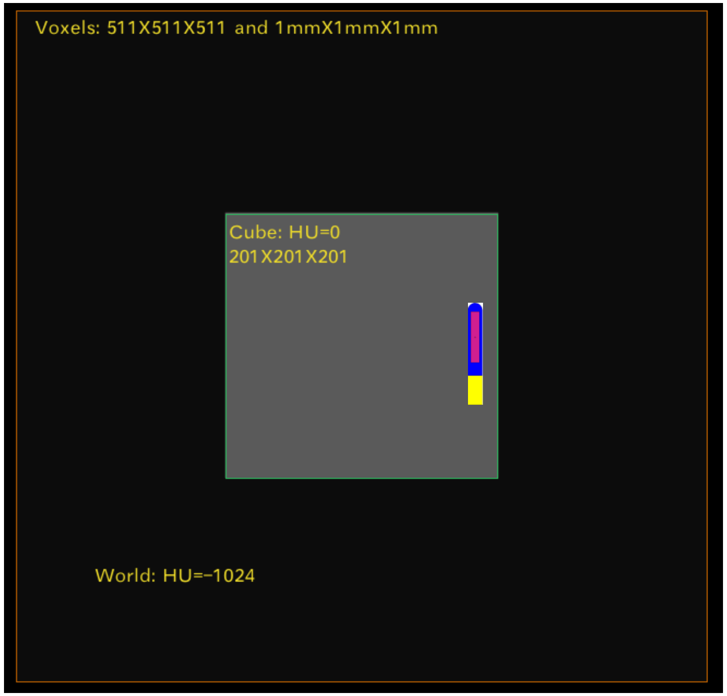
- Test case 2



(source not to scale)

Test cases

- Test case 3



- Test case 4

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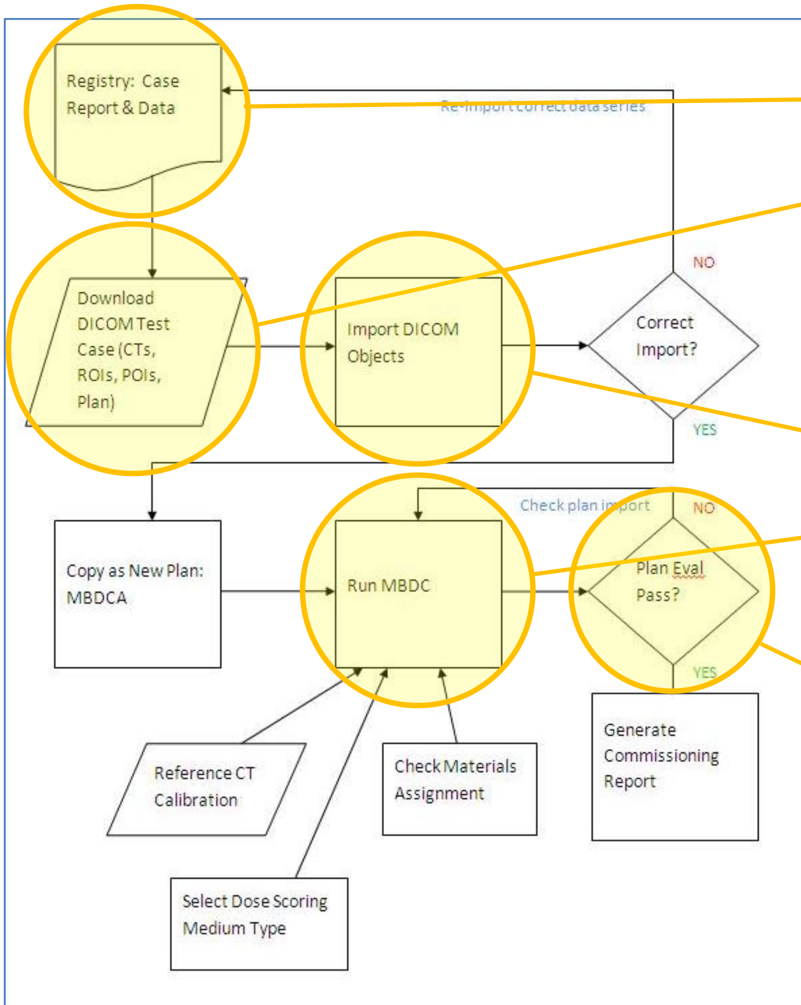
Commissioning Workflow



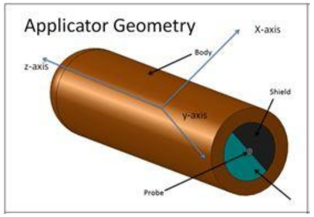
Abridged flowchart for MBDC software commissioning (adapted from TG-186).

1. *Access* the Registry
2. *Download (a)* a test plan and *(b)* MC reference dose distribution (DICOM)
3. *Import* DICOM objects
4. *Calculate* dose locally using the plan and MBDCA
5. *Compare & evaluate* MBDCA and reference dose distributions

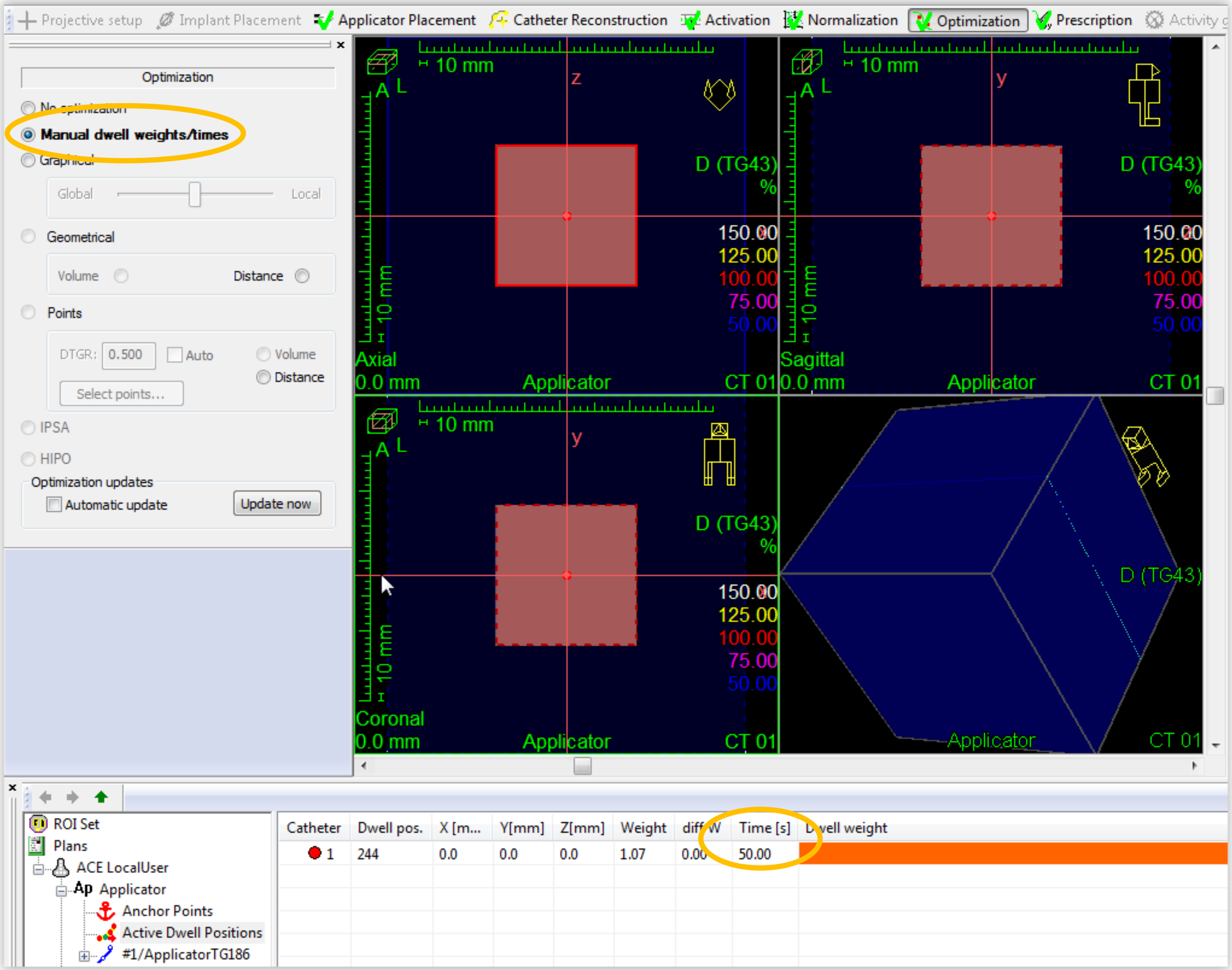
From R. Sloboda

Main Steps

Set up for local dose calculation



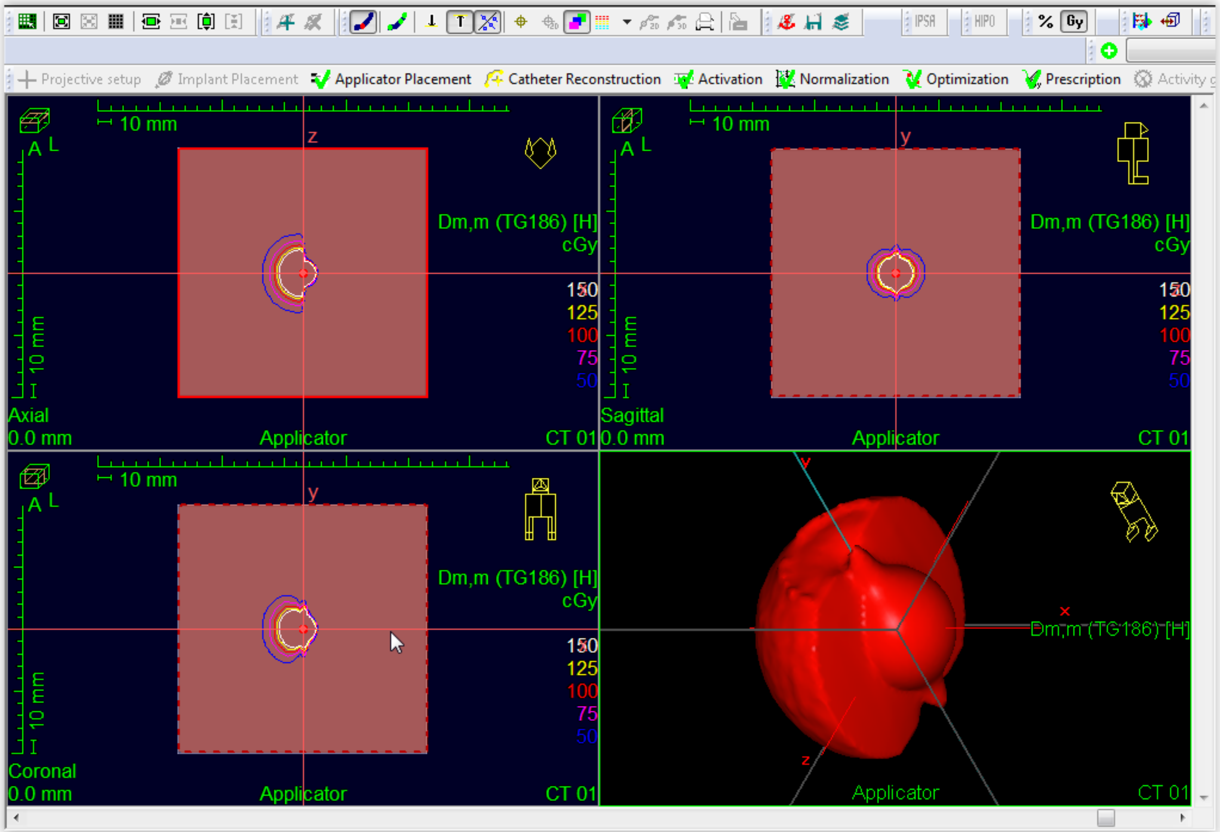
Case 4



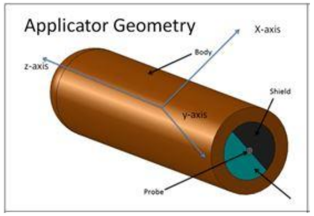
From Sloboda, 2017

Main Steps

4. Calculate dose locally using the MBDCA

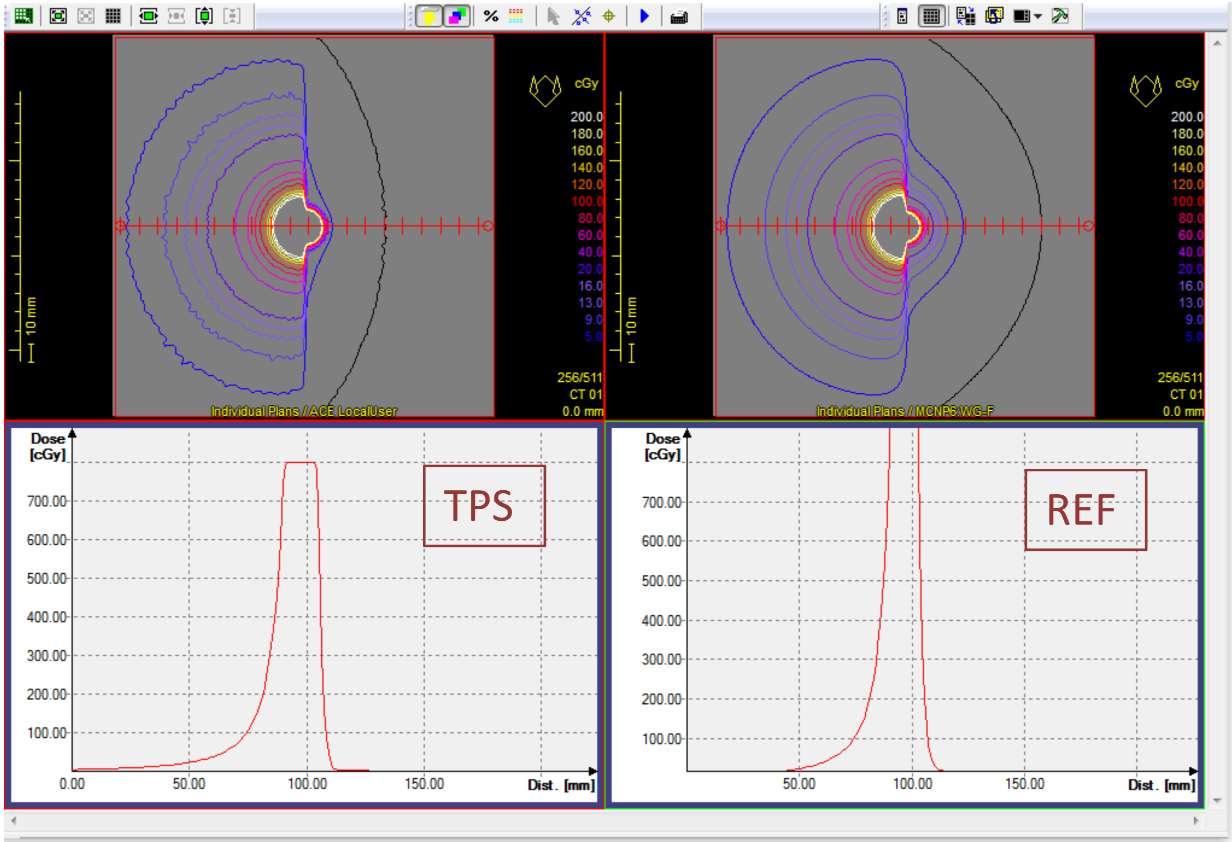


Case 4

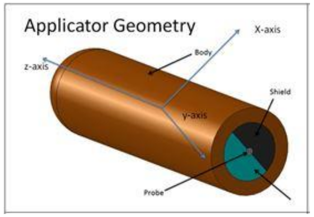


Main Steps

5. Compare & evaluate TPS and Ref. doses



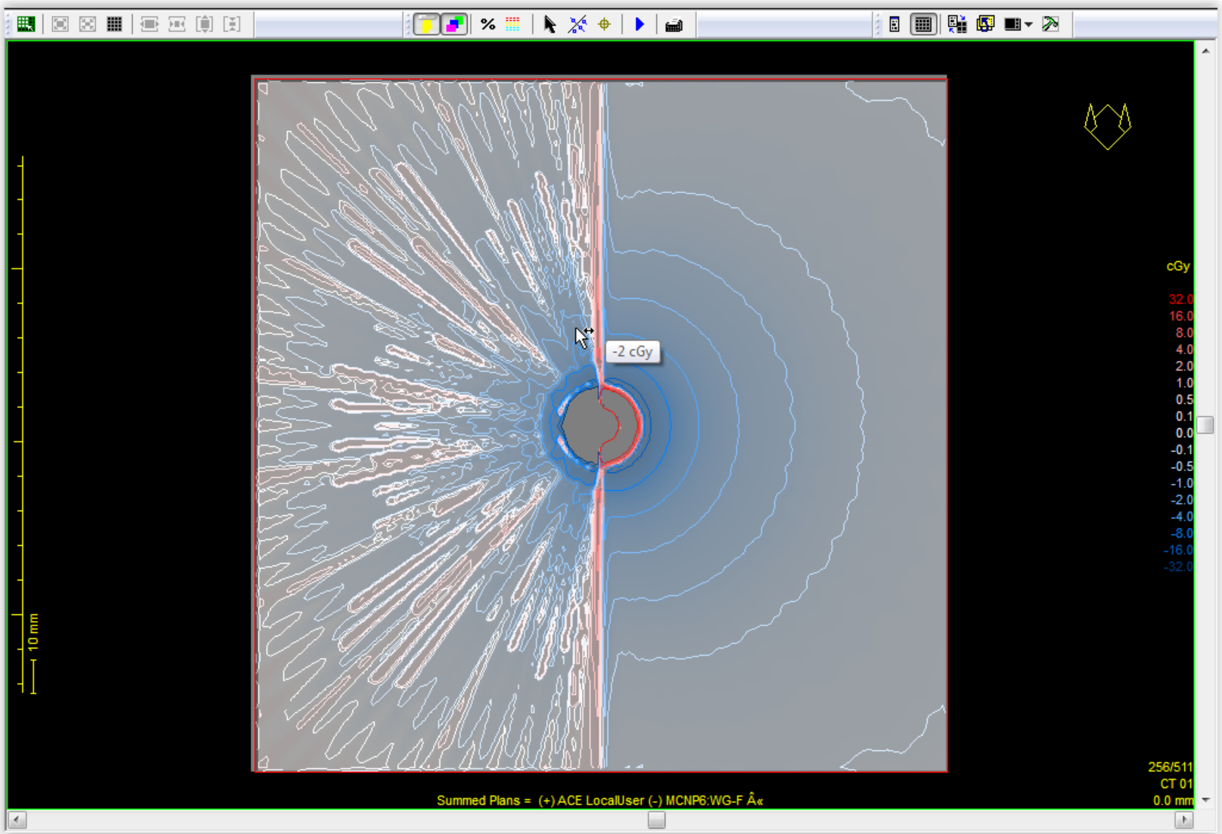
Case 4



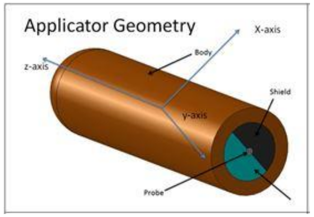
OCB dose profiles

Main Steps

OCB dose difference map, point dose query



Case 4

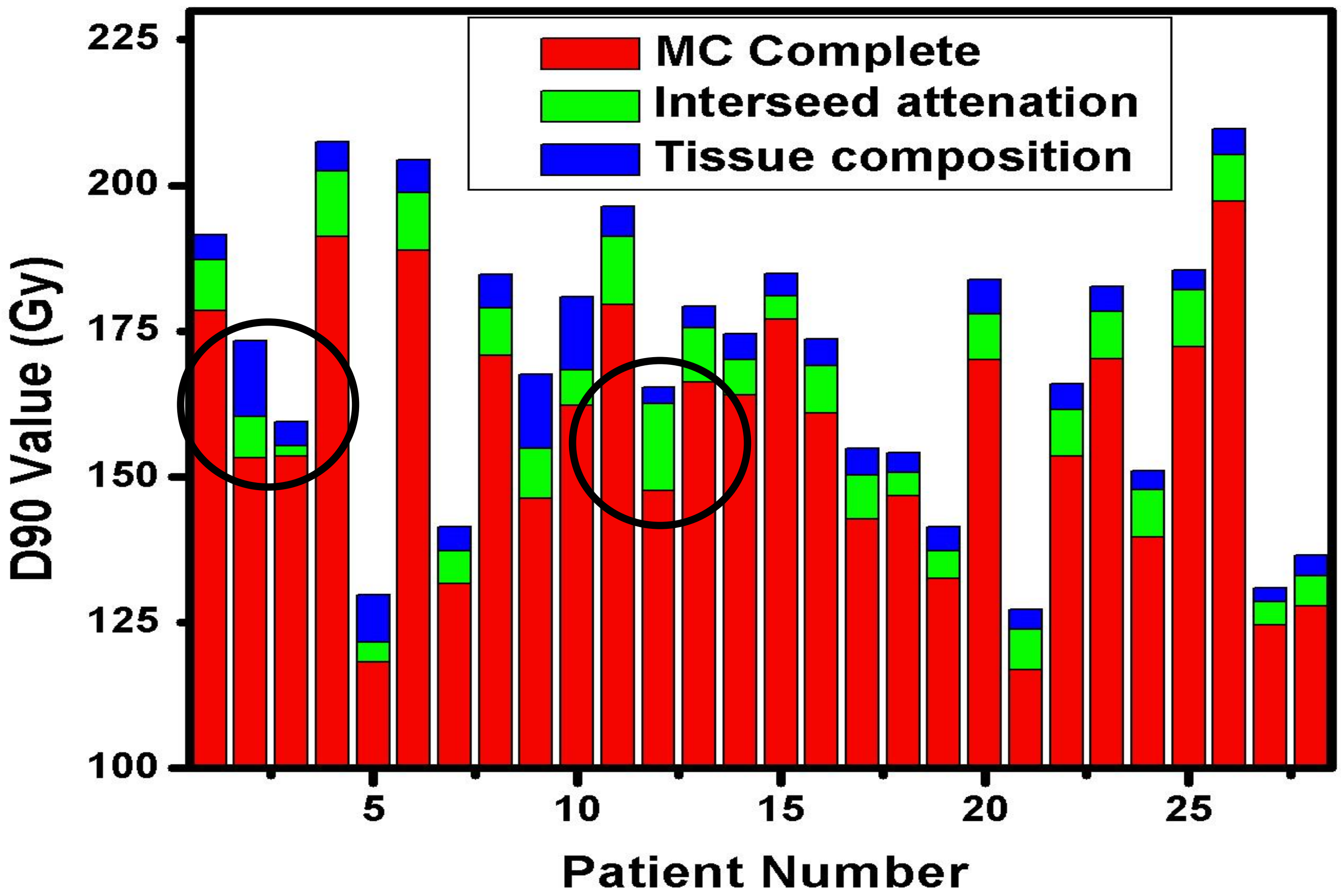


Does it make clinical differences?

The case of prostate calcifications:

LDR Seed Implants

PROSTATE LDR BRACHYTHERAPY

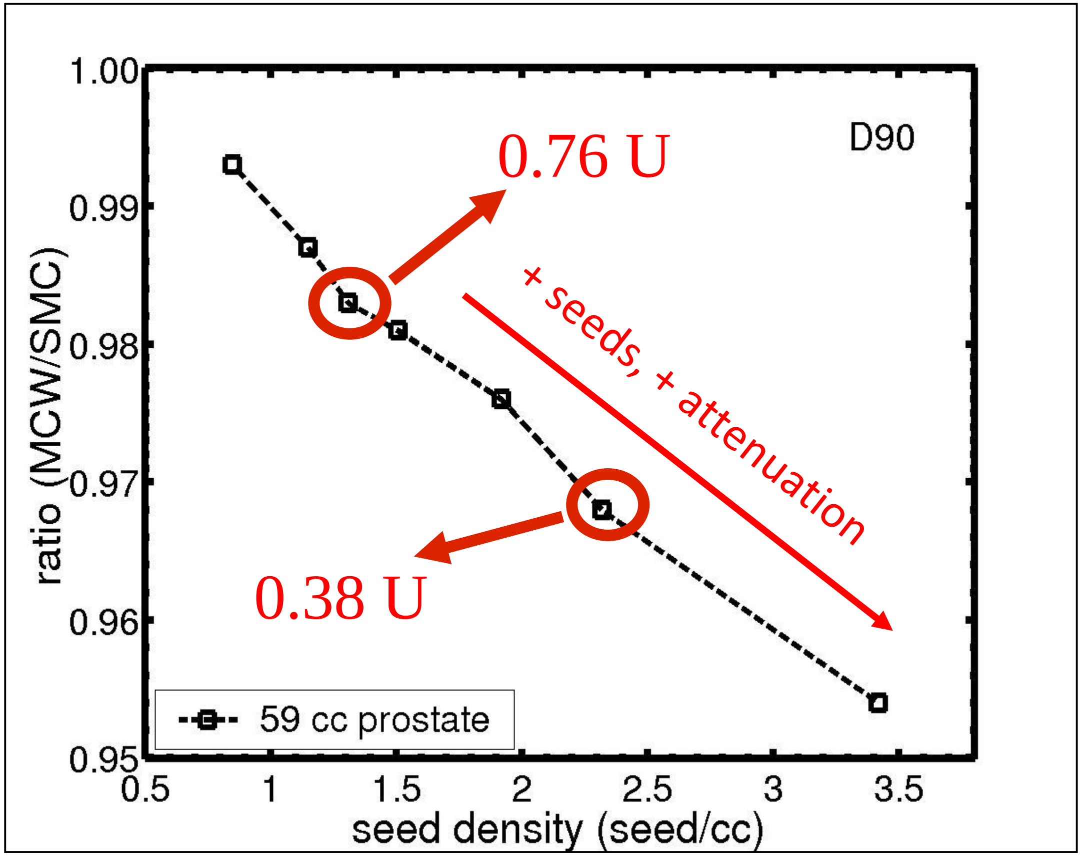


≈ 4% ↓

≈ 3% ↓

JF Carrier et al., IJROBP 2007

Interseed Attenuation



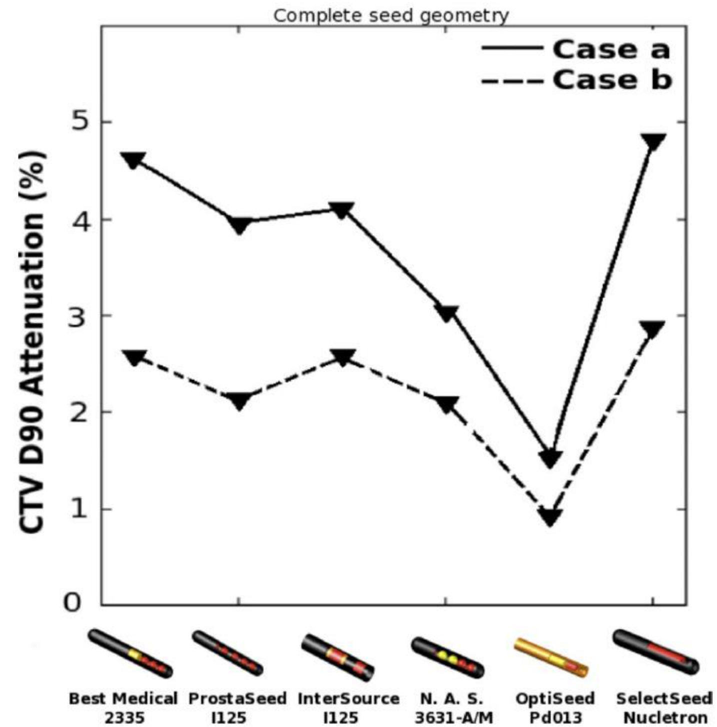
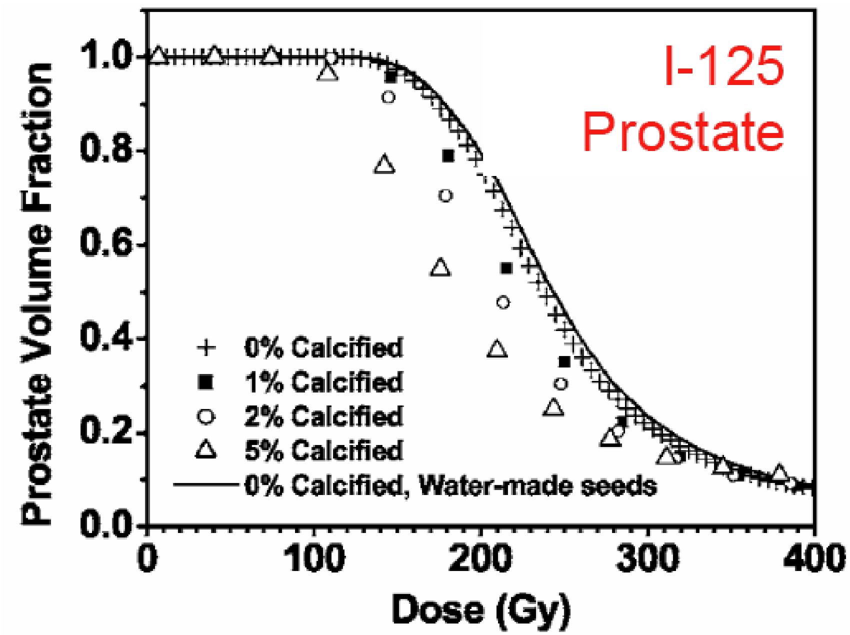


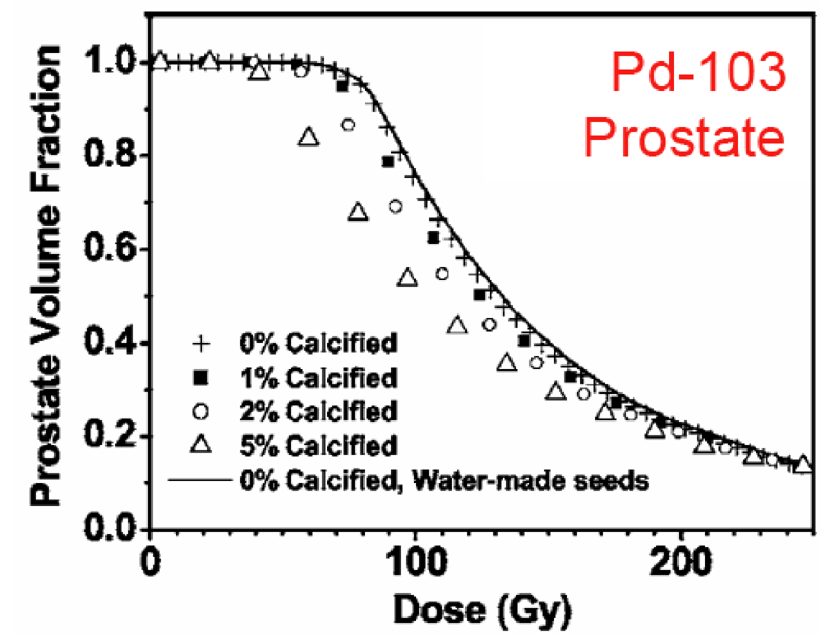
FIG. 7. D90 attenuation in two cases due to complete seed geometry.

JF Carrier et al., Med Phys 2006

Afsharpour et al., Med Phys 2008

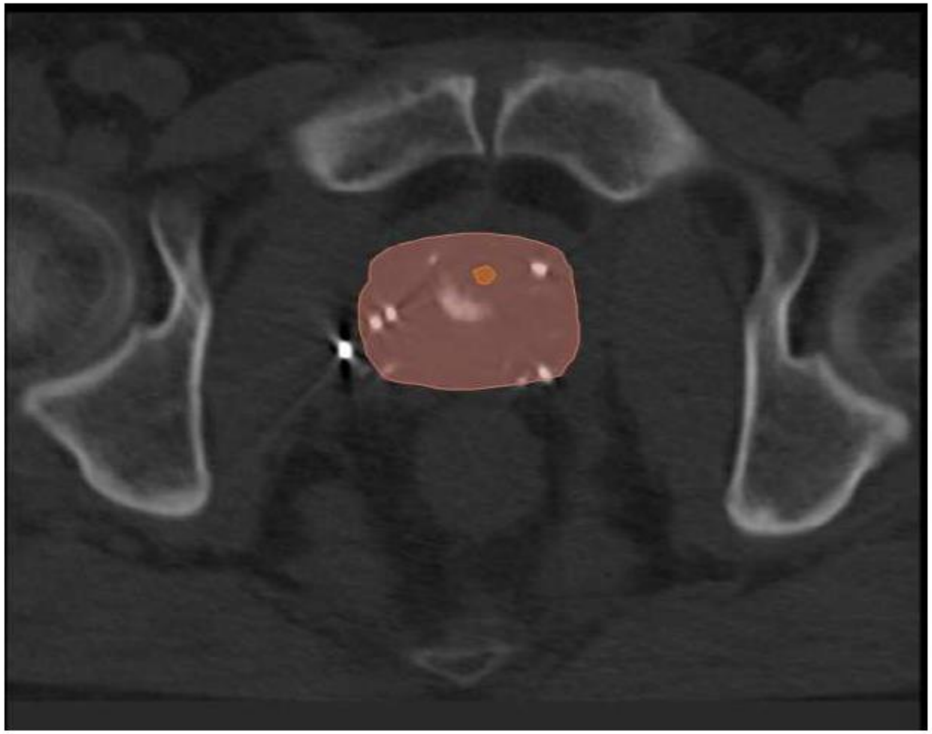
CALCIFICATIONS



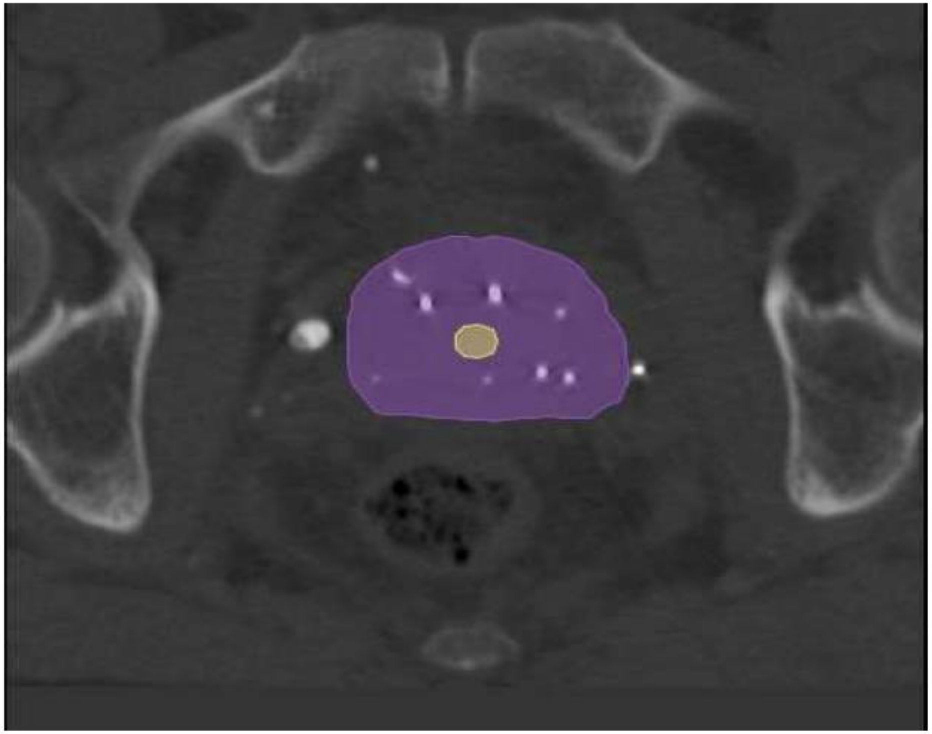


- Chibani & Williamson, Med. Phys. 2005

CALCIFICATIONS



(g) Significant calcification



(h) Typical patient

CA Collins-Fekete et al., Radiother Oncol 2014

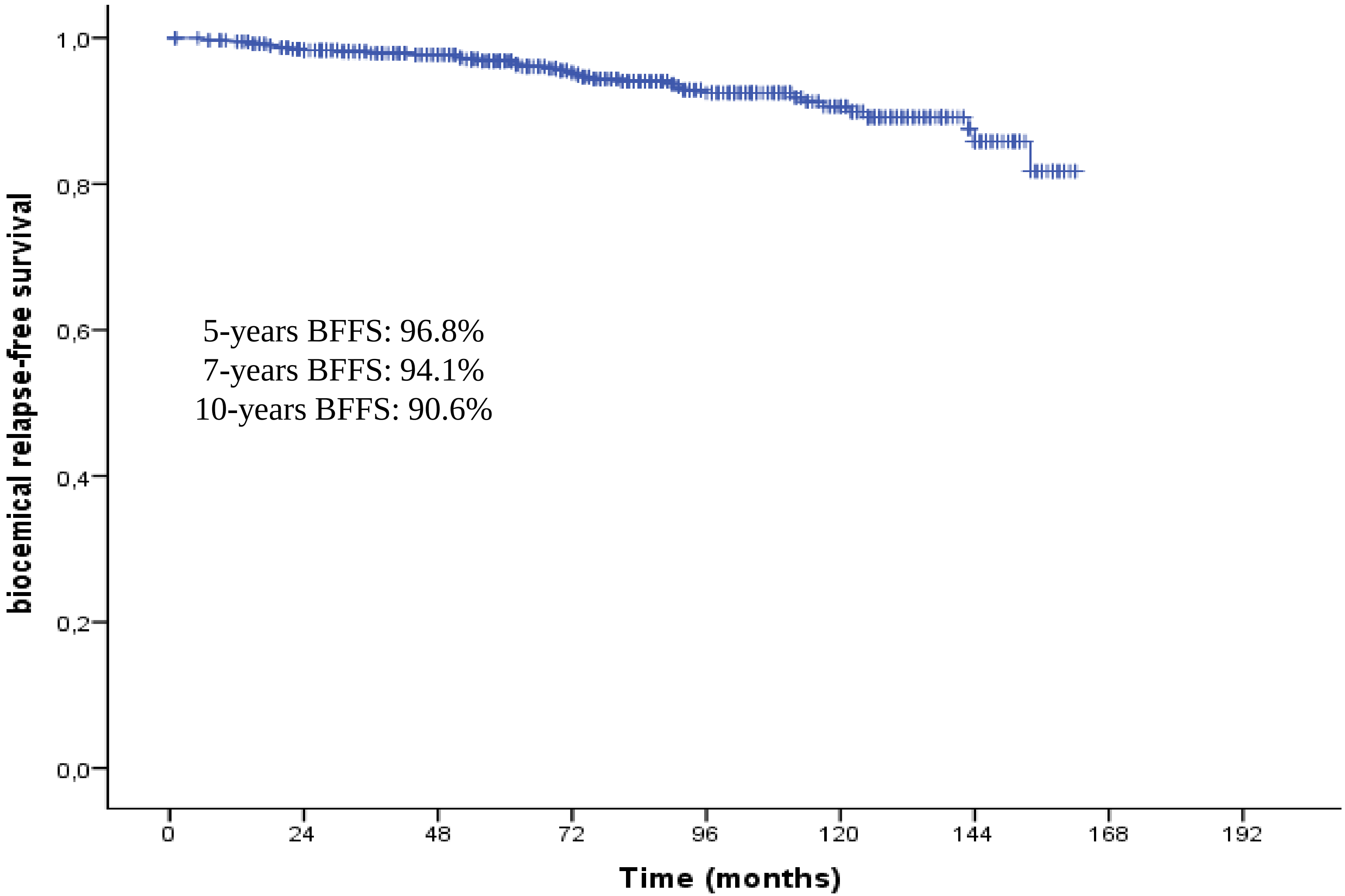
Retrospective Cohort

- CHU de Quebec performs seeds implants since 1994
- Needs patients with:
  - post-implant CT
  - DICOM-RT export

- 613 usable cases in the research database out of about 1500

Cohort: Martin *et al*, IJROBP **67** (2007): 334–41; Martell *et al*, IJROBP (2017) In Press.
Physics: Collins-Fekete *et al*, Rad Onc **114** (2015) 339-344; Miksys *et al* IJROBP **97** (2017) 606-615; Miksys *et al*, Med Phys **44** (2017) 4329-4340.

Outcome for this cohort: bRFS



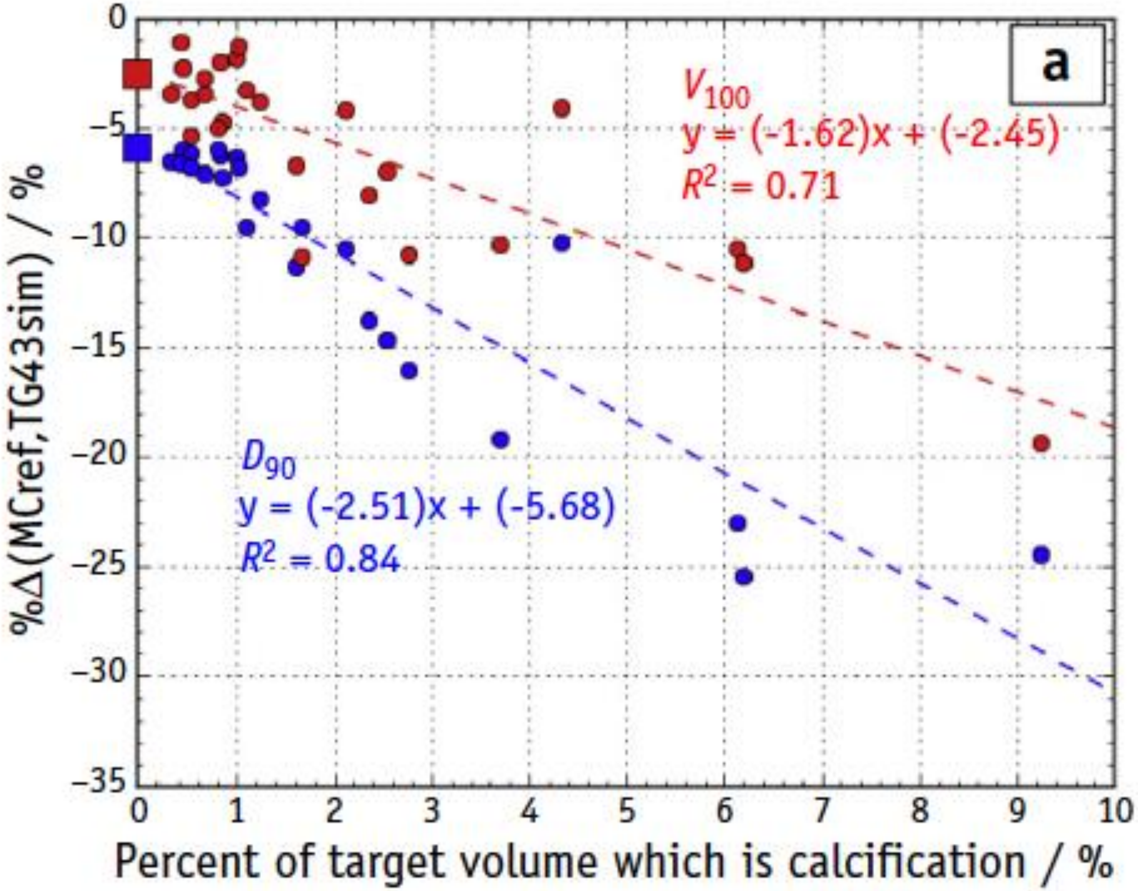
AVERAGE OF 42 SELECTED PATIENTS WITH VISIBLE CALCIFICATIONS

TABLE: Dosimetric indices differences to TG-43

	D_WATER	D_CALCI	D_FULL_MC
$D_{10\%}$	98.7±0.4	94.8±08.8	92.3±08.4
$D_{90\%}$	98.4±0.4	88.6±12.1	86.8±09.2
$V_{100\%}$	99.6±1.1	93.5±18.4	93.8±17.7
$V_{150\%}$	99.1±0.6	92.1±12.0	90.7±10.2
$V_{200\%}$	97.2±1.1	84.9±13.3	80.8±12.6

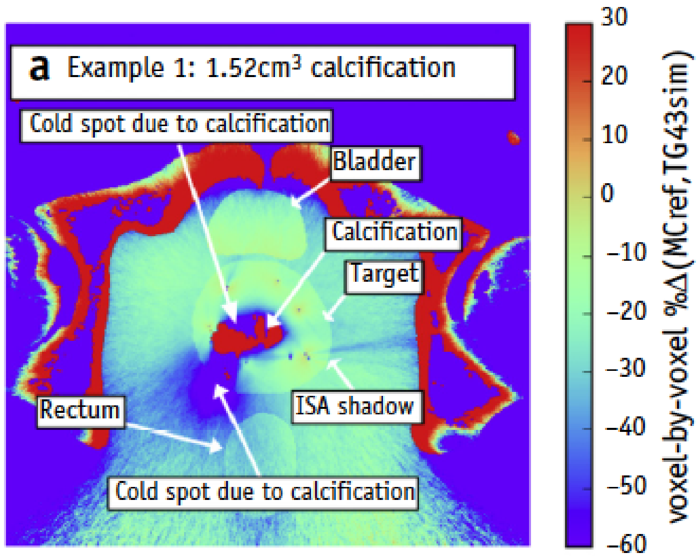
CA Collins-Fekete et al., Radiother Oncol 2015

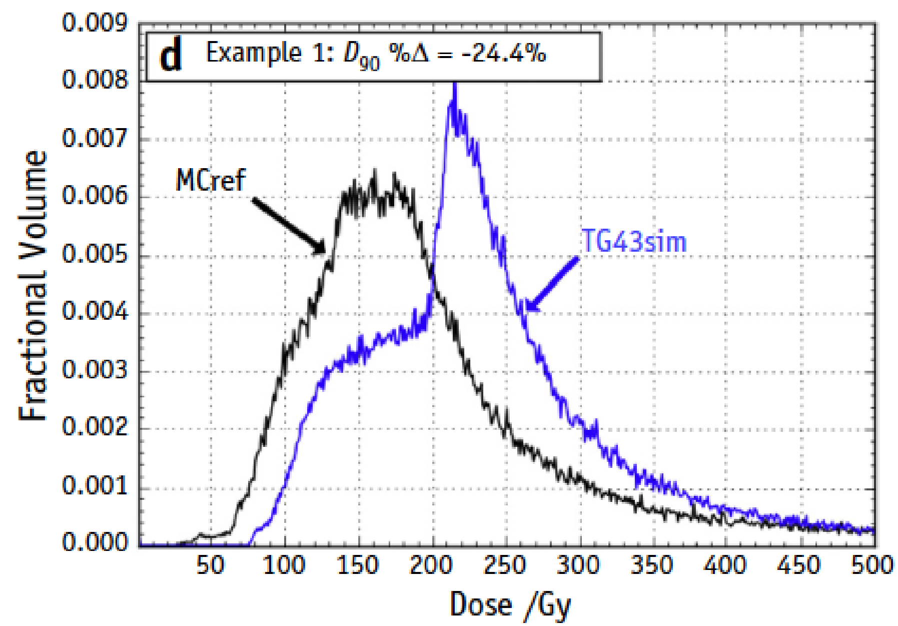
CALCIFICATIONS

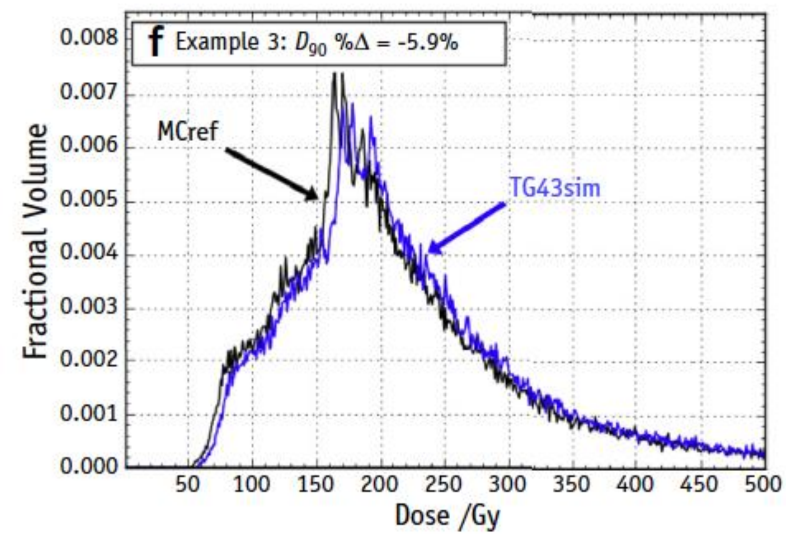


Miksys et al., IJROBP 97 (2017) 606-615

CALCIFICATIONS

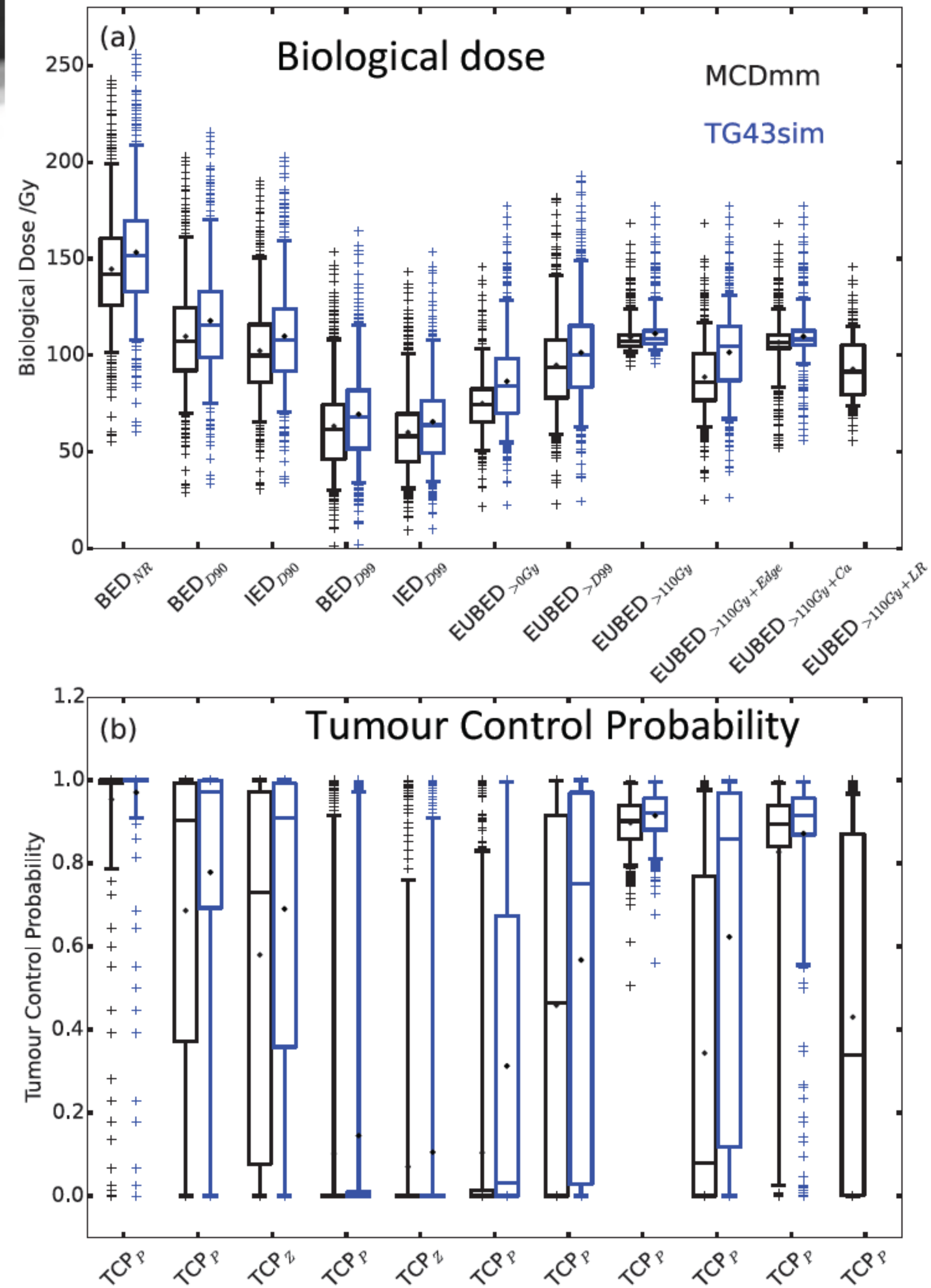






Miksys et al., IJROBP 97 (2017) 606-615

IMPACT ON RADIOBIOLOGICAL DOSE?



Summary of results

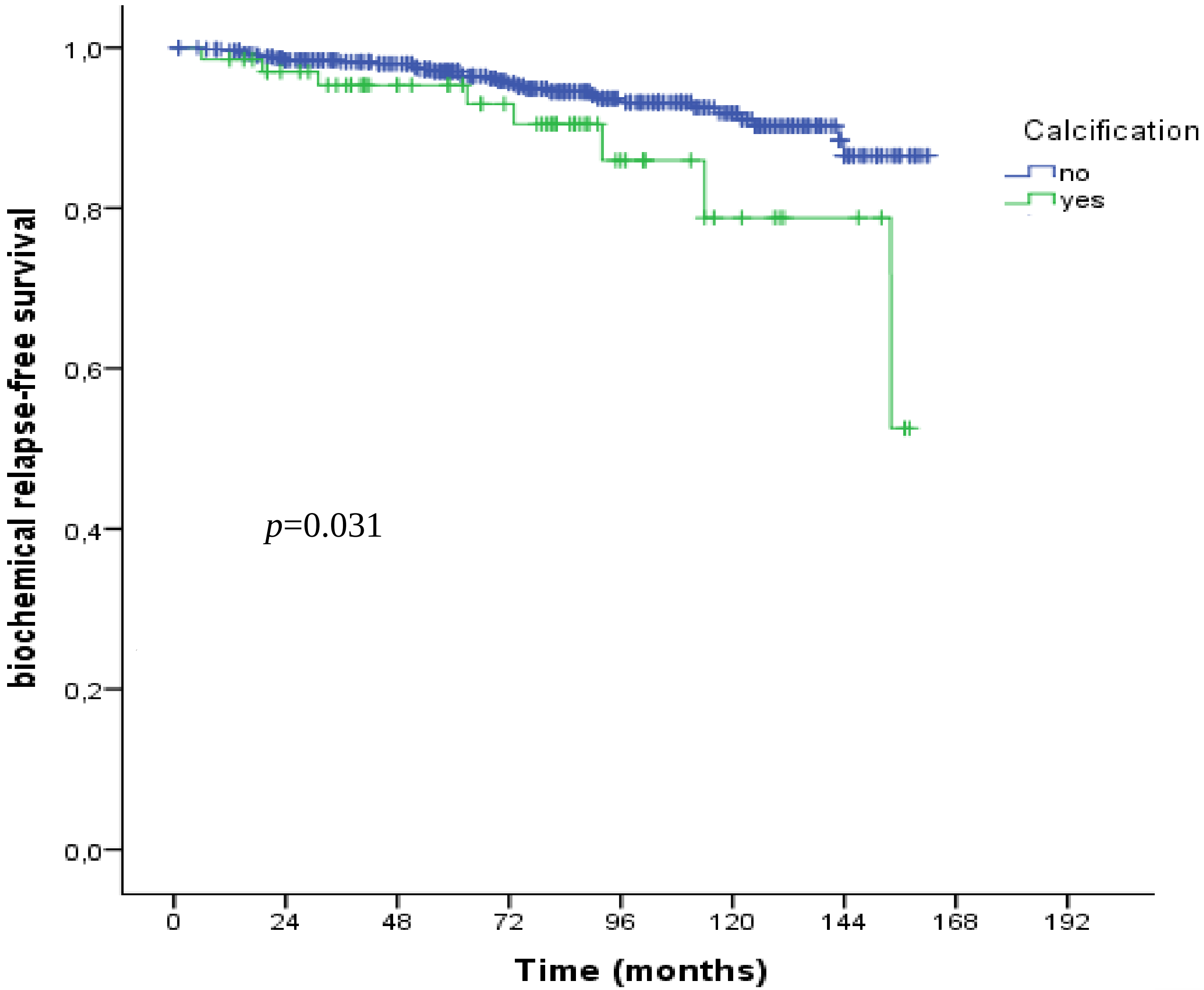
11 biological doses models (varying complexity) and corresponding TCP estimates

Radiobiological doses – also considered IED = Isoeffective dose [Zaider & Minerbo, PMB **45** (2000); Zaider & Hanin, PMB **52**, 6355 (2007)]

Miksys et al, Med Phys 2017

Slide by Rowan Thomson

Preliminary Results: bRFS



CONCLUSION

- Monte Carlo: essential for clinical adoption of MBDCA
- NextGEN Brachytherapy needs MC
  - R&D, validation, …
- Better dose calculations do make a difference
  - Dose-outcome relationships
  - Radiobiology
  - …

Grazie!

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