Why do we need treatment verification and *in vivo* dosimetry

Braphyqs & GEC-ESTRO Seminar on On-Line Treatment Verification: In Vivo Dosimetry and Computational Methods for Brachytherapy

Brussels 2014

Kari Tanderup and Gustavo Kertzscher

Organisors

- Gustavo Kertzscher, MD Anderson, USA
- Dimos Baltas, Offenbach, Germany
- Frank André Siebert, Kiel, Germany
- Kari Tanderup, Aarhus, Denmark

- ESTRO office
  - Evelyn Chimfwembe
  - Melissa Vanderijst

- Supported by:

Eckert & Ziegler ELEKTA VARIAN medical systems

79 participants from 21 countries

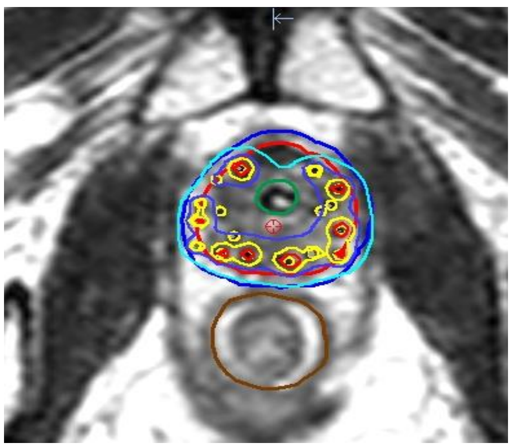
Programme

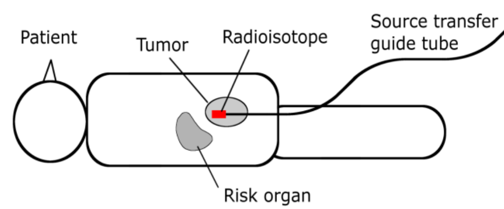
Braphyqs & GEC-ESTRO Seminar on On-Line Treatment Verification: ***In Vivo*** Dosimetry and Computational Methods for Brachytherapy
Monte Carlo Meeting Room - 4th floor in the ESTRO Office, Avenue E. Mounierlaan 44, 1200 Brussels, Belgium
December 5, 2014

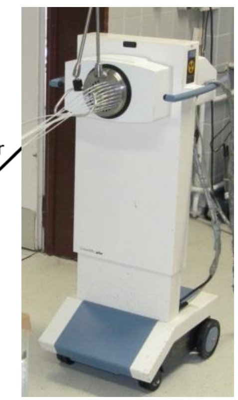
TIME	TOPIC	SPEAKER
8:15 - 8:45	**Welcome and introduction: Why do we need treatment verification and *in vivo* dosimetry?**	Kari Tanderup (Denmark)
8:45 - 9:40	**TREATMENT VERIFICATION**	**chair: Frank-André Siebert (Germany)**
(20 min)	*In vivo* dosimetry in real time	Gustavo Kertzscher (USA)
(20 min)	Computational Verification (CoVer)	Dimos Baltas (Germany)
(15 min)	Discussion	
9:40 - 10:10	**BREAK**	
10:10 - 12:10	**IN VIVO VERIFICATION TECHNOLOGY AND CONCEPTS - MAJOR CHALLENGES & OPPORTUNITIES (10 + 5 min / presenter)**	**chair: Jack Venselaar (The Netherlands)**
	Development of multiple-points PSD for *in vivo* dosimetry	Luc Beaulieu (Canada)
	Development of real-time *in vivo* dosimeters using radiochromic material and optical fibers	Alexandra Rink (Canada)
	Physical characterization of a Ce3+ doped SiO2 optical fibre for *in vivo* dosimetry in HDR brachytherapy	Mauro Carrara (Italy)
	Real-time *in vivo* dosimetry using radioluminescence of pre-irradiated Al2O3:C crystals	Gustavo Kertzscher (USA)
	MOSFET applications in brachytherapy	Joanna Cygler (Canada)
	Patient treatment verification by direct *in vivo* source position determination in HDR brachytherapy	Ryan Smith (Australia)
	Exploring position verification of an Ir-192 source with MRI	Rien Moerland (The Netherlands)
	In vivo dosimetry with PSDs to monitor the rectal dose during EBRT and the prospects for HDR brachytherapy	Sam Beddar (USA)
12:10 - 13:10	**LUNCH**	
13:10 - 14:20	**EFFORTS AND EXPERIENCES IN THE CLINIC (7 + 4 min / presenter)**	**chair: Luc Beaulieu (Canada)**
	Initial work towards the clinical implementation of IVD in brachytherapy at Mount Vernon Cancer Centre	Aaron Huckle (UK)
	Interstitial irradiation of mamma carcinoma: First results with MOSFET *in vivo* dosimetry	Corinna Melchert (Germany)
	Implementing real-time MOSFET *in vivo* dosimetry for HDR prostate brachytherapy	Joshua Mason (UK)
	MOSkin dosimeters integrated to a transrectal-US probe for *in vivo* dosimetry in HDR prostate brachytherapy	Mauro Carrara (Italy)
	Clinical experience with simple *in vivo* dosimetry for rectum and bladder	Nicole Nesvacil & Christian Kirisits (Austria)
	Status of IVD for brachytherapy in France	Estelle Spasic (France)
14:20 - 14:50	**BREAK**	
14:50 - 15:35	**HOW COULD WE TACKLE BIG CHALLENGES?**	**chair: Dimos Baltas (Germany)**
(15 min)	Translational research & open source gateway	Francois Therriault-Proulx (USA)
(15 min)	Are collaborations and verification important for overcoming big challenges in brachytherapy?	Gustavo Kertzscher (USA)
(15 min)	Discussion	
15:35 - 16:20	**GROUP DISCUSSION**	**chair: Kari Tanderup (Denmark)**
(15 min)	Comprehensive Verification: treatment planning QA + IVD + imaging	Kari Tanderup (Denmark)
(30 min)	Discussion - selected topics	

Treatment verification

- Planned dose is delivered to the patient







Treatment decision
Recording
Patient chart

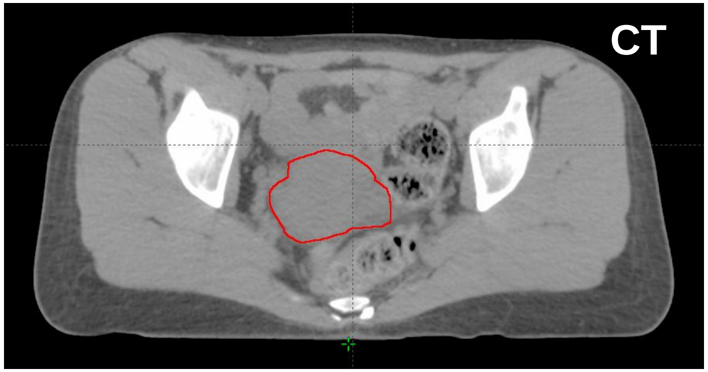
?

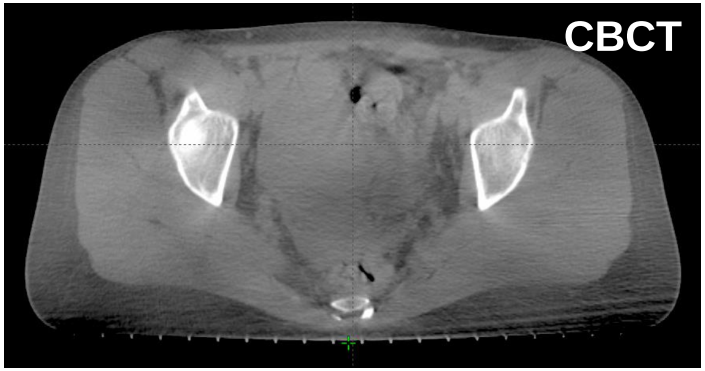
Errors and uncertainties

- Errors/misadministrations
  - Treatment incidents which can be prevented
- Uncertainties
  - Can be controlled to a certain degree
  - Residual variation must be taken into account e.g. through tolerances and margins

Treatment delivery verification EBRT

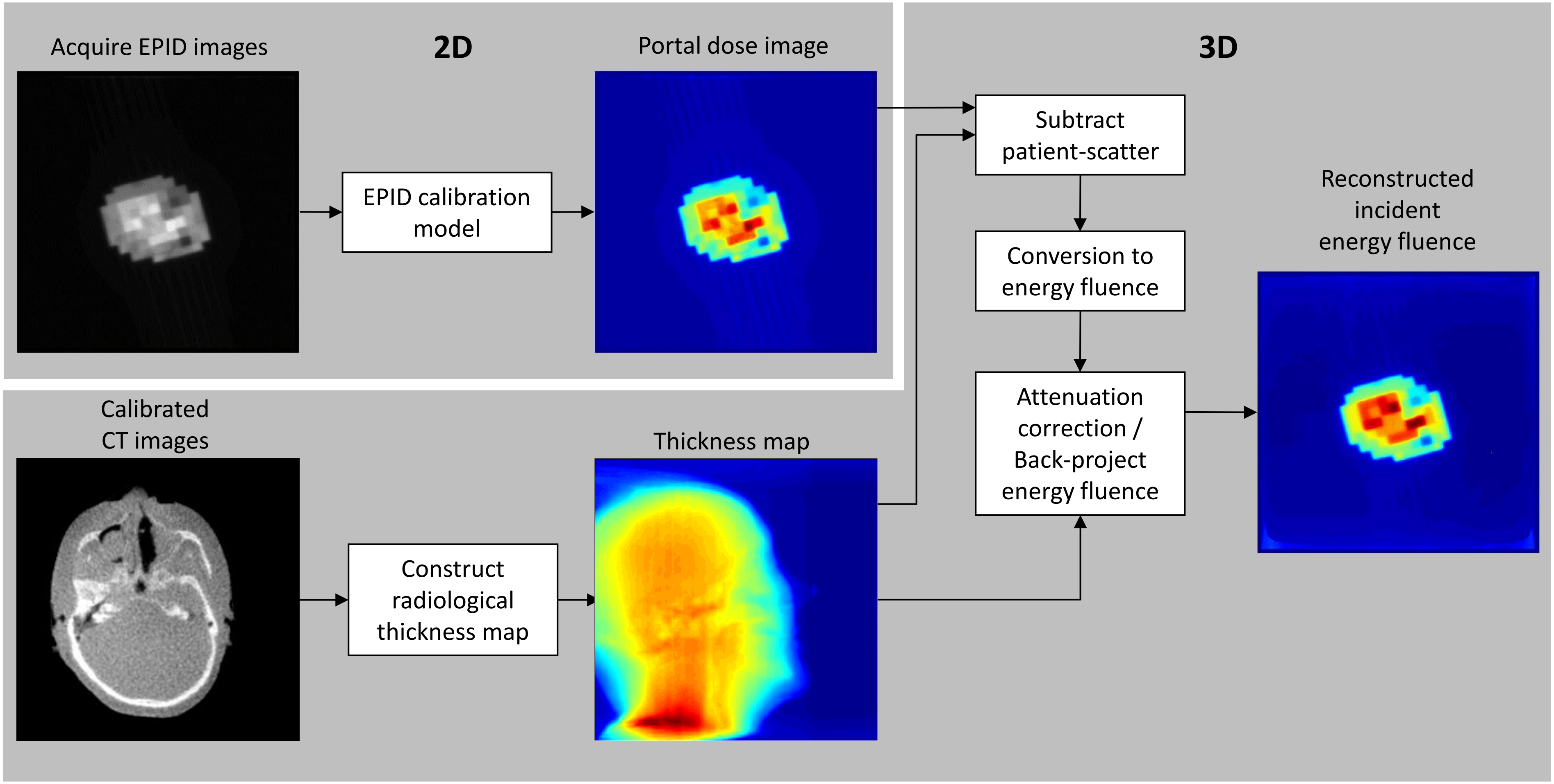
- On board imaging (2D and 3D):
  - decreasing uncertainties
- Real time EPID dosimetry:
  - errors and uncertainties
- Real time in vivo dosimetry (Beddar):
  - errors and uncertainties





3D EPID dosimetry

Courtesy Lucas Persson, MAASTRO

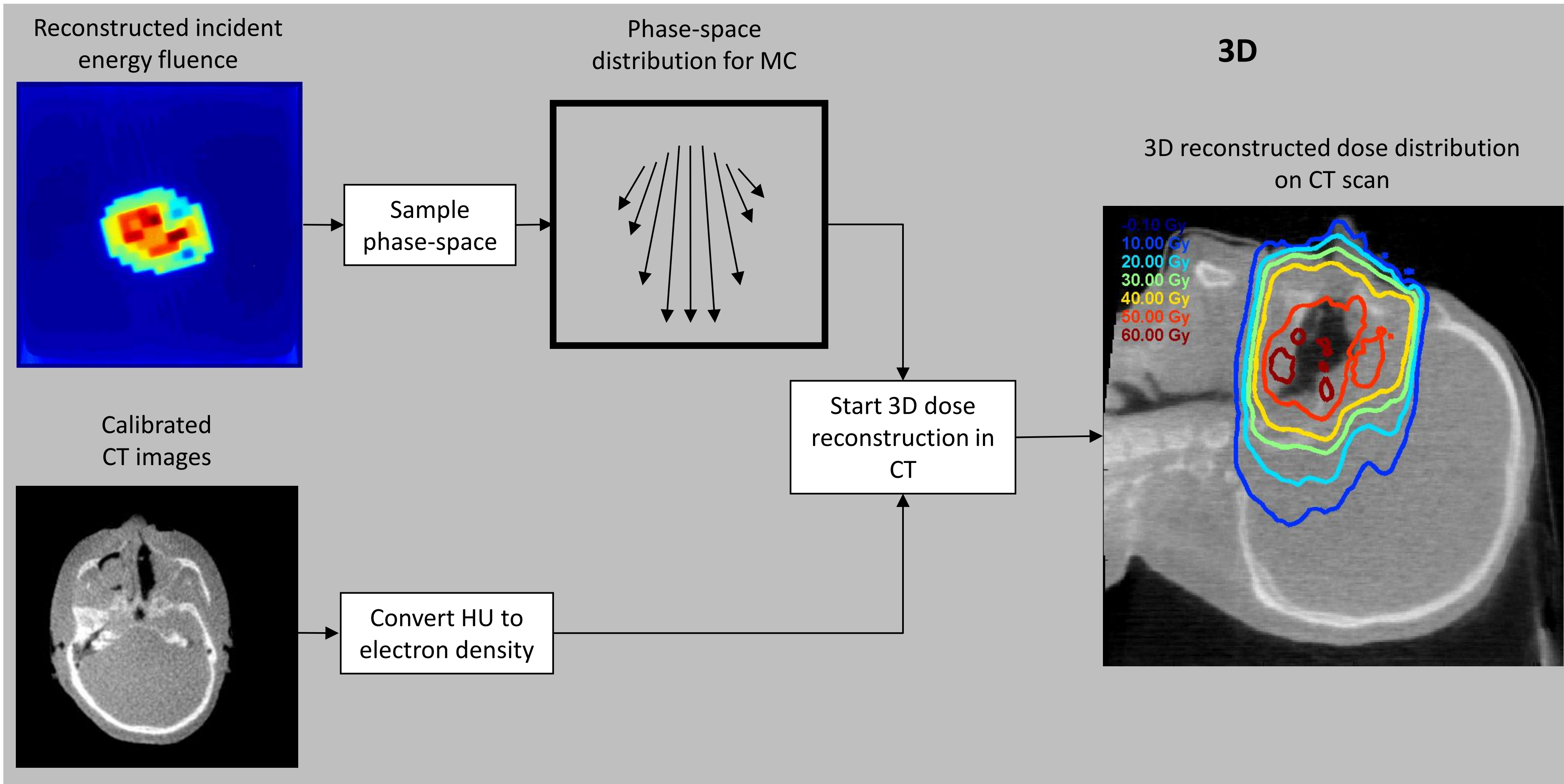


van Elmpt et al., A Monte Carlo based three-dimensional dose reconstruction method, Med. Phys. 33(7), 2006
Nijsten et al., A global calibration model for a-Si EPIDs used for transit dosimetry, Med. Phys. 34(10), 2007

EPID dosimetry @ MAASTRO CLINIC

Courtesy Lucas Persson, MAASTRO

2D and 3D verification methods

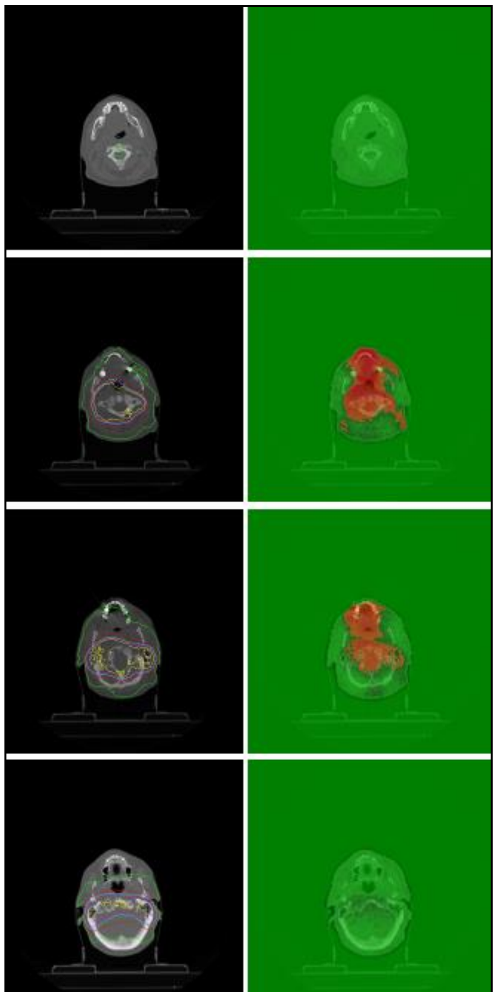


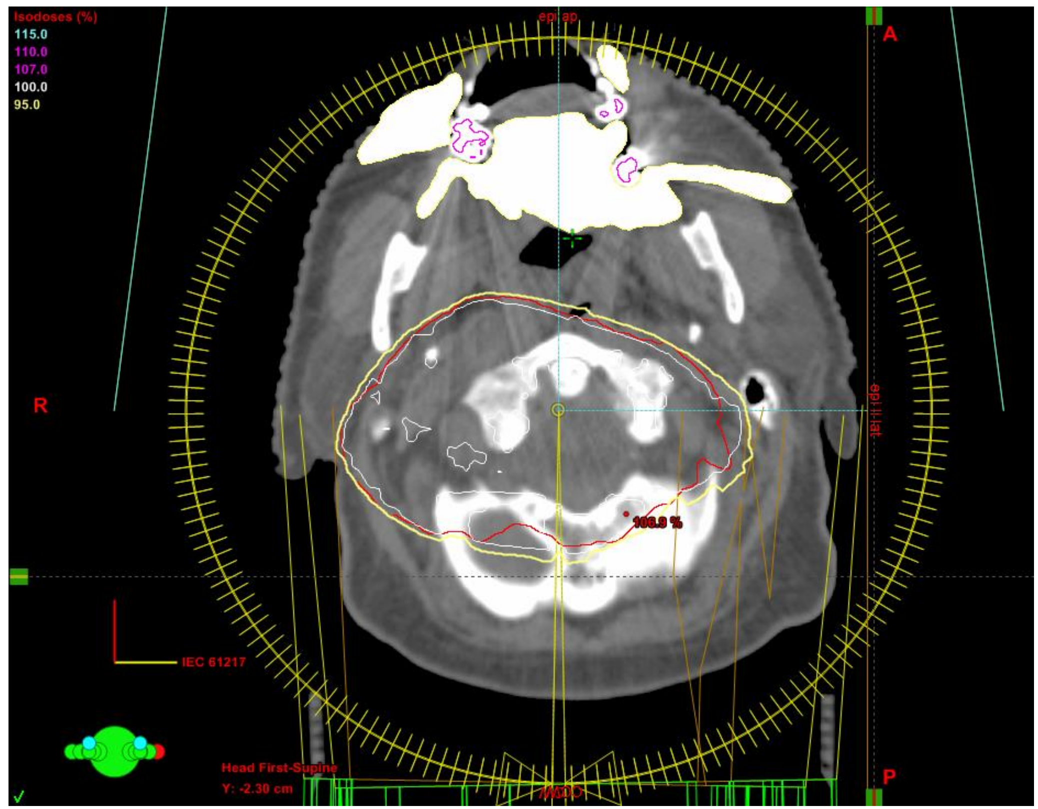
van Elmpt et al., A Monte Carlo based three-dimensional dose reconstruction method, Med. Phys. 33(7), 2006

Nijsten et al., A global calibration model for a-Si EPIDs used for transit dosimetry, Med. Phys. 34(10), 2007

3D dose verification for H&N cancer treatment

Dose differences due to erroneous forced density value during treatment planning





Courtesy Lucas Persson, MAASTRO

Treatment delivery verification in brachytherapy

- On-board imaging?
  - Few institutions and publications

- Dosimetry?
  - Patterns of care on availability of in vivo dosimetry
    - 2002: 80 of the 348 centres with BT (23%)
    - 2007: 77 of the 339 centres with BT (24%)

- Real time dosimetry?
  - Experimental

Guedea F et al. Radiother Oncol. 2007 Jan;82(1)
Guedea F et al. Brachytherapy. 2008 Jul-Sep;7(3):223-30.

Pubmed search

- ”In vivo dosimetry radiotherapy”: 1551 hits
- ”In vivo dosimetry brachytherapy”: 133 hits

Importance of treatment verification for brachytherapy

- ”High” risk of errors (as compared to EBRT):
  - Manual procedures: reconstruction of catheters, applicator afterloader connection, applicator length
  - ”Mechanical” equipment: cables, transfer tubes, applicators

- High impact of errors/uncertainties:
  - High dose gradients
  - Hypofractionation

- Challenge: Low patient volume (as compared to EBRT):
  - Investment
  - Expertise (small clinics)

Incidence reports – what do we have?

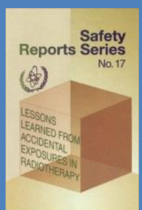
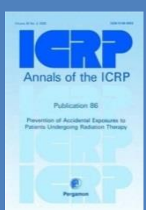
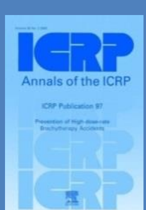
- Non-exhaustive reviews representing error types (ICRP, IAEA)
- International databases for recording of incidents and near-incidents
- National databases on occurences: systematic reporting of incidents and near-incidents

Not so recent reports

- IAEA Safety Report Series 17. **"Lessons learned from accidental exposures in radiotherapy"**, Vienna, Austria: IAEA. IAEA Safety Reports Series (2000).
- P.O. Lopez, P. Andreo, J.-M. Cosset, A. Dutreix, T. Landberg, **"Prevention of accidental exposures to patients undergoing radiation therapy"**, ICRP Publications 86, Annals of the ICRP. New York, NY: Pergamon (2000).
- L. P. Ashton, J.-M. Cosset, V. Levin, A. Martinez, S. Nag, **"Prevention of high-dose-rate brachytherapy accidents"**, ICRP Publications 97, Annals of the ICRP. New York, NY: Pergamon (2004).

Not so recent reports

NOTE: events do overlap

REPORT (year)	OBJECTIVE	SCOPE	TREATMENT MODALITIES
IAEA (2000) 	1. Provide basis for safety improvements in institutions 2. Encourage questioning and learning attitude	Non-exhaustive review of **published** radiotherapy events, representing a wide range of error types	EBRT, **LDR BT (N=28),** **HDR BT (N=3),** nuclear medicine
ICRP (2000) 	Assist in prevention of accidental exposures during EBRT and BT	1. Description of illustrative severe accidents (case histories) 2. Discussion of causes & contributing factors 3. Summary of consequences 4. Recommendations (preventions)	EBRT, LDR+HDR (N=33)
ICRP (2004) 	1. Review reported accidents and the lessons learned 2. Address measures to minimize risk of unfortunate events	HDR BT Not intravascular BT Focus on ^{192}Ir sources (not ^{60}Co)	HDR BT, ***number of events not quantified***

Quality item	Detectability	
	Real-time IVD	Real-time imaging
Source calibration	✓[b]	
Afterloader source positioning and dwell time (non-patient specific)[c]	✓[d]	
Afterloader malfunction	✓[d]	
Patient identification		✓[e]
Correct treatment plan	✓[f]	
Intra- and interfraction organ/ applicator movement[c]	✓[d,g]	✓
Applicator reconstruction and fusion errors	✓[d,h]	✓
Applicator length/source indexer length	✓[d,i]	
Source step size (patient specific)	✓[d,i]	
Interchanged guide tubes	✓[d]	
Recording of dose[c]	✓[j]	

K. Tanderup, S. Beddar, C. E. Andersen, G. Kertzscher, J. E. Cygler, **“*In vivo* dosimetry in brachytherapy”**, Med. Phys. 40(7), 070902 (15 pp.) (2013).

G. Kertzscher, A. Rosenfeld, S. Beddar, K. Tanderup, J. E. Cygler, **“*In vivo* dosimetry: trends and prospects for brachytherapy”**, Br. J. Radiol. 87, 20140206 (16 pp.) (2014).

Not so recent reports

QUALITY ITEM	IAEA (2000)	ICRP (2000)	ICRP (2004)	DETECTABILITY	
Number of HDR/PDR events	**3 (HDR)**	**? (HDR)**	**? (HDR)**	**IVD**	**IMAGING**
Source calibration		33 BT events are classified into categories (Table 3), however, **A)** nature of events are not described in detail, **B)** no info whether LDR or HDR	✓	✓	
Afterloader source positioning and dwell time			✓	✓	
Afterloader malfunction	1		✓	✓	
Patient identification	1		✓		✓
Correct treatment plan				✓	
Intra- and interfraction organ/applicator movement				✓	✓
Applicator reconstruction and fusion errors			✓	✓	✓
Applicator length/source-indexer length			✓	✓	
Source step size (patient specific)			✓	✓	
Interchanged guide tubes			✓	✓	
Recording of dose				✓	
Other (e.g. defective catheter)	1		✓	?	?

Not so recent reports

QUALITY ITEM	IAEA (2000)	ICRP (2000)	ICRP (2004)	DETECTABILITY	
				IVD	IMAGING
Number of HDR/PDR events	3 (HDR)	? (HDR)	? (HDR)		
Source calibration		33 BT events are classified into categories (Table 3), … LDR or HDR	✓	✓	
Afterloader source positioning and dwell time			✓	✓	
Afterloader malfunction	1		✓	✓	
Patient identification	1		✓		✓
Correct treatment plan				✓	
Intra- and interfraction organ/applicator movement				✓	✓
Applicator reconstruction and fusion errors				✓	✓
Applicator length/source-indexer length				✓	
Source step size (patient specific)				✓	
Interchanged guide tubes				✓	
Recording of dose				✓	
Other (e.g. defective catheter)	1		✓	?	?

Several other categories, e.g.

- Dislodged applicator
- Kink in catheter
- Wrong orifice
- Failure of retraction system
- …

More recent reports – U.S. NRC

- More recent reports can be found by the United States Nuclear Regulatory Commission
- The scope of NRC reports are similar to those of IAEA and ICRP, and includes radiotherapy in general (EBRT and BT)
- We looked at reports from 2010 – 2013, and searched for treatments accidents related to afterloaded HDR BT

U.S. NRC. Report to Congress on Abnormal Occurrences (NUREG-0090) [accessed November 23 2014]. Available from http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0090/

More recent reports: 2005-2013

QUALITY ITEM	U.S. Nuclear Regulatory Commission	DETECTABILITY	
Number of HDR/PDR events	17 (HDR)	IVD	IMAGING
Source calibration		✓	
Afterloader source positioning and dwell time		✓	
Afterloader malfunction		✓	
Patient identification			✓
Correct treatment plan		✓	
Intra- and interfraction organ/applicator movement	1	✓	✓
Applicator reconstruction and fusion errors	4	✓	✓
Applicator length/source-indexer length	5	✓	
Source step size (patient specific)		✓	
Interchanged guide tubes		✓	
Recording of dose		✓	
Other (e.g. defective catheter)	7	?	?

More recent reports: 2005-2013

QUALITY ITEM	U.S. Nuclear Regulatory Commission	DETECTABILITY	
		IVD	IMAGING
Number of HDR/PDR events	17 (HDR)		
Source calibration		✓	
Afterloader source positioning and dwell time		✓	
Afterloader malfunction			
Patient identification			✓
Correct treatment plan			
Intra- and interfraction organ/applicator movement			✓
Applicator reconstruction and fusion errors			✓
Applicator length/source-indexe length			
Source step size (patient specific			
Interchanged guide tubes			
Recording of dose		✓	
Other (e.g. defective catheter)	7	?	?

<u>Examples – all (in principle) detectable:</u>

- Wrong guide tube, 12 cm too short
- Obstructed GYN catheter for HDR (60 Gy to skin between thighs)
- Inverted catheter direction (not detected by planners nor TPS)
- Catheter not fully inserted into tandem
- Radiation therapist pushed “auto radiography” rather than “treatment” button → 9 times the intended dose
- Incorrect target area entered into HDR device

QA and verification

How **<u>quality assurance (QA)</u>** could be interpreted:

- ***Procedures with specific preventive actions*** against compromised quality of the treatment, errors, misadministration, incidents and near-incidents
- Applied ***in the clinical setting*** throughout all stages of the treatment, from source installation to patient follow-up
- Should be applied also ***during treatment delivery, hence <u>online verification should be employed</u>***

Why is in vivo dosimetry not systematically used?

Routine rectal in vivo dosimetry, Aarhus University Hospital:

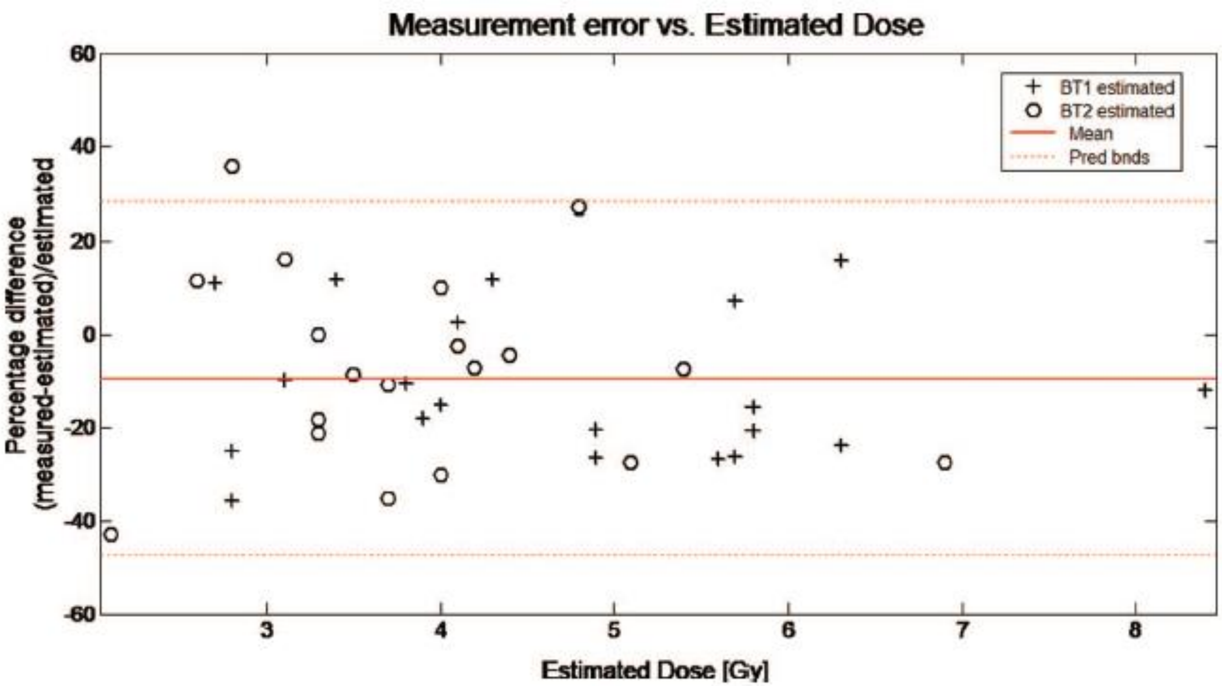
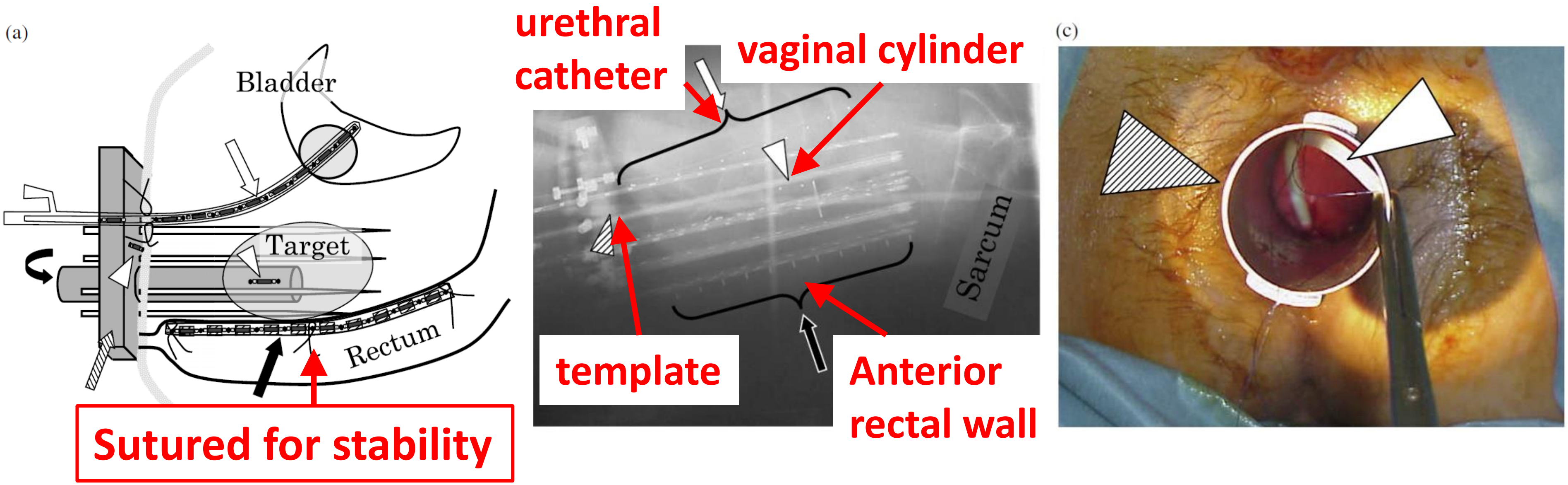


FIG. 1. Rectal IVD in PDR ^{192}Ir cervix cancer BT with tandem ring applicator for BT fractions 1 (BT1) and 2 (BT2). Dashed lines indicate bounds of the 95% prediction interval.

Tanderup, Beddar, Andersen, Kertzscher, Cygler. In vivo dosimetry in brachytherapy, Med Phys 40(7), 2013

Passive dosimetry

- Nose et al. (2008): interstitial HDR (pelvic malignancy)
  - Large data set: **66 patients, 1004 dosimetry points**
  - ***Still, the IVD publication with largest #patients*** *(to our knowledge)*
  - Several dosimetry sites: **rectum, urethra, target, perineum**
- Purpose: ***investigate reproducibility*** of pelvic interstitial HDR



T. Nose, M. Koizumi, K. Yoshida et al., ***"In vivo*** **dosimetry of high-dose-rate interstitial brachytherapy in the pelvic region: use of radiophotoluminescence glass dosimeter for measurement of 1004 points in 66 patients with pelvic malignancy"**, Int. J. Radiat. Oncol. Biol. Phys. 70, 626-33 (2008).

Int. J. Radiation Oncology Biol. Phys., Vol. 70, No. 2, pp. 626–633, 2008

0360-3016/08/$–see front matter

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doi:10.1016/j.ijrobp.2007.09.053

Conclusions: Deviations between measured and calculated doses for the rectum and urethra were greater than 20%, which is attributable to the independent movements of these organs and the applicators. Missing corrections

PHYSICS C

IN VIVO DOSIMETRY OF HIGH-DOSE-RATE INTERSTITIAL BRACHYTHERAPY IN THE PELVIC REGION: USE OF A RADIOPHOTOLUMINESCENCE GLASS DOSIMETER FOR MEASUREMENT OF 1004 POINTS IN 66 PATIENTS WITH PELVIC MALIGNANCY

Takayuki Nose, M.D.,[*†] Masahiko Koizumi, M.D.,[‡] Ken Yoshida, M.D.,[§] Kinji Nishiyama, M.D.,[‡] Junichi Sasaki,[‡] Takeshi Ohnishi,[‡] Takuyo Kozuka, M.D.,[*] Kotaro Gomi, M.D.,[*] Masahiko Oguchi, M.D.,[*] Iori Sumida, Ph.D.,[*†] Yutaka Takahashi, Ph.D.,[†] Akira Ito, Ph.D.,[†] and Takashi Yamashita, M.D.[*†]

Int. J. Radiation Oncology Biol. Phys., Vol. 73, No. 1, pp. 314–321, 2009

0360-3016/09/$–see front matter

doi:10.1016/j.ijrobp.2008.08.040

mined in a simulation experiment, is 8.0% (1 SD). *In vivo* dose values were obtained for 17 patients. In the high-dose region (> 100 Gy), calculated and measured dose values agreed within 1.7% ± 10.7% (1 SD). In the low-dose region outside the prostate (< 100 Gy), larger deviations occurred.

IN VIVO DOSIMETRY USING A LINEAR MOSFET-ARRAY DOSIMETER TO DETERMINE THE URETHRA DOSE IN ^{125}I PERMANENT PROSTATE IMPLANTS

Esther J. Bloemen-van Gurp, M.A., Lars H. P. Murrer, Ph.D., Björk K. C. Haanstra, Francis C. J. M. van Gils, M.D., Ph.D., Andre L. A. J. Dekker, Ph.D., Ben J. Mijnheer, Ph.D.,

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compared to calculated doses by the treatment planning system (TPS). The differences between calculated and measured dose ranged from 8.5% to 41.2%. This corresponds to absolute dose differences

Technical notes

Comparison of planned and measured rectal dose *in-vivo* during high dose rate Cobalt-60 brachytherapy of cervical cancer

Z.K. Zaman [a, b], N.M. Ung [a, b, *], R.A. Malik [b], G.F. Ho [b], V.C.E. Phua [b], Z. Jamalludin [a, b], M.T.H. Baharuldin [d], K.H. Ng [a, c]

Int. J. Radiation Oncology Biol. Phys., Vol. 79, No. 2, pp. 609–615, 2011

0360-3016/$–see front matter

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doi:10.1016/j.ijrobp.2010.03.030

Results: Improvements to the system design allowed for accurate dose measurements to be made *in vivo*. A maximum measured dose departure of 9% from the calculated dose was observed after dosimeter design improvements.

CLINICAL TRIALS OF A URETHRAL DOSE MEASUREMENT SYSTEM IN BRACHYTHERAPY USING SCINTILLATION DETECTORS

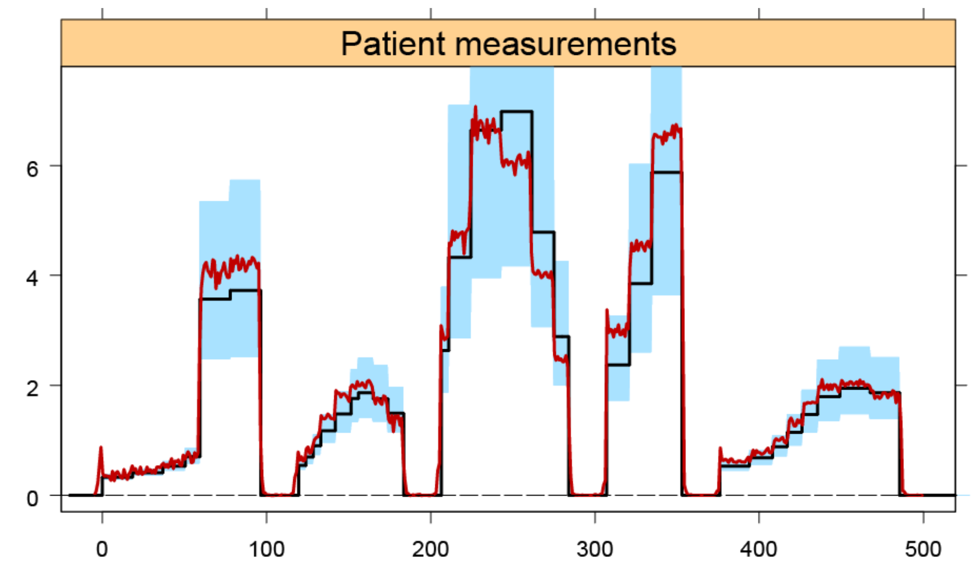
Natalka Suchowerska, Ph.D.,[*†] Michael Jackson, FRANZCR., M.B., B.Chir.,[‡§] Jamil Lambert, Ph.D.,[†] Yong Bai Yin, Ph.D.,[†] George Hruby, FRANZCR.,[*§] and David R. McKenzie, Ph.D.[†]

How do we make progress?

From integral dose to dose rate

From off line to on-line

- Organ dose measurements not primary objective
- Main purpose: QA of treatment progression
- Instantaneous error detection
- Improved sensitivity



Real-time dosimetry

Published **real-time** *in vivo* dosimetry studies – all 3 of them

Article	Treatments	Dosimeter placement	Results	Abnormal deviations from treatment plan? Reason? *(if yes)*
Tanderup et *al.* (2006)	PDR GYN, **10 patients**	Rectum	Organ-applicator movements	No.
Andersen et *al.* (2009)	PDR GYN, **5 patients**	Interstitial needles	Monitoring of real-time dose rates & accumulated dose	Yes. Probable mis-placed dosimeter probe.
Suchowerska et al. (2011)	HDR prostate **24 patients**	Urethra		Yes.

K. Tanderup, J. Juul Christensen, J. Granfeldt, J. C. Lindegaard, **"Geometric stability of intracavitary pulsed dose rate brachytherapy monitored by *in vivo* rectal dosimetry"**, Radiother. Oncol. 79, 87-93 (2006).

C. E. Andersen, S. Kynde Nielsen, J. C. Lindegaard, K. Tanderup, **"Time-resolved *in vivo* luminescence dosimetry for online detection in pulsed dose-rate brachytherapy"**, Med. Phys. 36, 5033-43 (2009).

N. Suchowerska, M. Jackson, J. Lambert, Y. B. Yin, G. Hruby, D. R. McKenzie, **"Clinical trials of a urethral dose measurement system in brachytherapy using scintillation detectors"**, Int. J. Radiat. Oncol. Biol. Phys. 79, 609-15 (2011).

What do we need?

- Overview of errors and frequencies
- Detectors:
  - Small detectors
  - Sensitive detectors
  - Real time dosimetry
  - Large dynamic range
  - Dose linearity
- Error detection algorithms
- Efficient cost-effective workflow