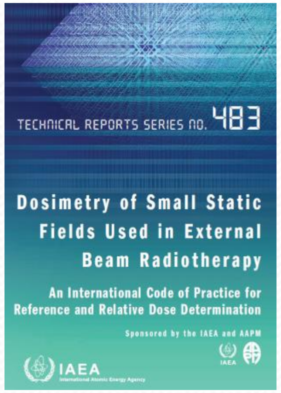
Implementation of IAEA TRS 483 in small field dosimetry of Leksell Gamma Knife Icon – transition from IAEA TRS 398 to IAEA TRS 483



Josef Novotný, Ph.D.

Plan for the lecture

- Brief introduction and dosimetry characteristics of Leksell gamma knife
- Small field dosimetry issues in general
- Situation in Leksell gamma knife dosimetry (now) and before IAEA TRS 483
- Transition to IAEA TRS 483 on Leksell Gamma Knife: reference dosimetry and relative dosimetry
- Dosimetry audit
- Conclusions and summary

BRIEF INTRODUCTION AND DOSIMETRY

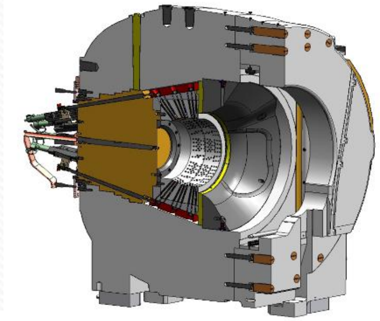
CHARACTERISTICS OF LEKSELL GAMMA KNIFE

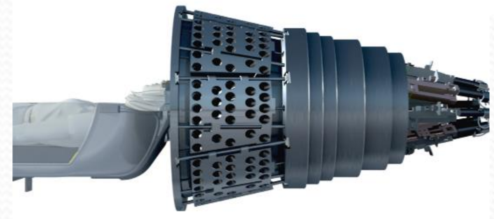
Leksell Gamma Knife Perfexion™ and Icon™

– 4, 8, 16 mm collimators

– 192 Co-60 sources (on 8 independent sectors)

– Cylindrical source geometry





Leksell Gamma Knife Perfexion™

Leksell Gamma Knife Icon™
(CBCT imaging option, mask fixation)

Only treatment of the head region

– intracranial targets (malignant, benign tumors, vascular and functional targets)

– extracranial targets (e.g. chemodectoma, limit C1)

– ophthalmoradiosurgery (e.g. uveal melanoma)

Leksell stereotactic frame (majority of patients)

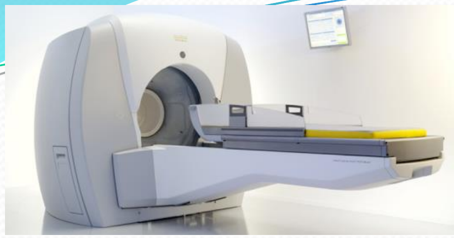
Mask fixation

SMALL FIELD DOSIMETRY ISSUES IN GENERAL

Small field dosimetry issues

- Technology evolution much faster than basic science and experimental measurement radiation physics
- Radiotherapy physics community was not prepared for the increased use of small fields for patient treatment
- Same existing calibration protocols and similar detectors have been used as in conventional radiotherapy (field size 40x40 mm^2 – 400x400 mm^2 compare to very small radiosurgery beams as small as 4 mm)

Radiosurgery and stereotactic radiotherapy technology



ELEKTA
Leksell Gamma Knife Perfexion

ELEKTA
Leksell Gamma Knife Icon

American Radiosurgery
RGS Vertex 360

American Radiosurgery
RGS Orbiter

ViewRay Co-60 System

Brainlab Novalis

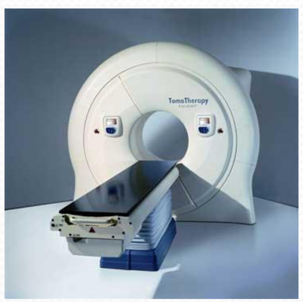
Varian Trilogy

Varian Truebeam

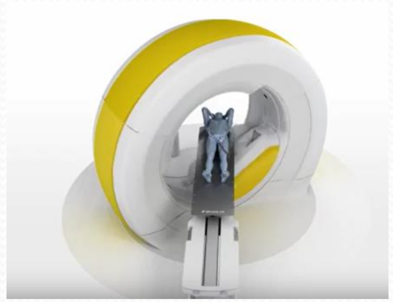
Elekta Axesse™

ViewRay MRIdian

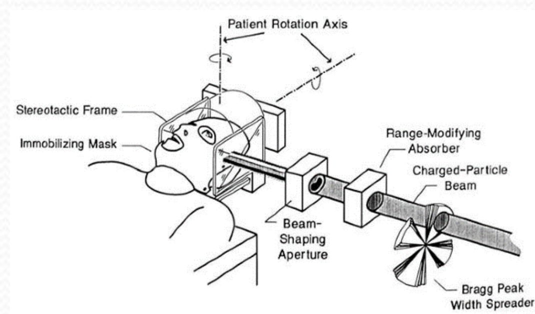
Accuray CyberKnife



Accuray Tomotherapy



VERO Brainlab-Mitsubishi



Heavy charged particles

ZAP-X

Challenges and issues in small field related to…

- Beams (Fields)
- Machines
- Detectors
- Treatment planning systems
- Measurements
- Dosimetry errors
- Relative dosimetry (Output factors)
- A new methodology for reference dosimetry

What is small and what is big in dosimetry?!

- Currently very subjective with no clear definition
- Commonly a field size of les than 3.0 x 3.0 cm^2

What is small field?

- There are essentially three "equilibrium factors" that determine the scale if a radiation field is to be considered as small or not

Small fields: Nonequilibrium radiation dosimetry

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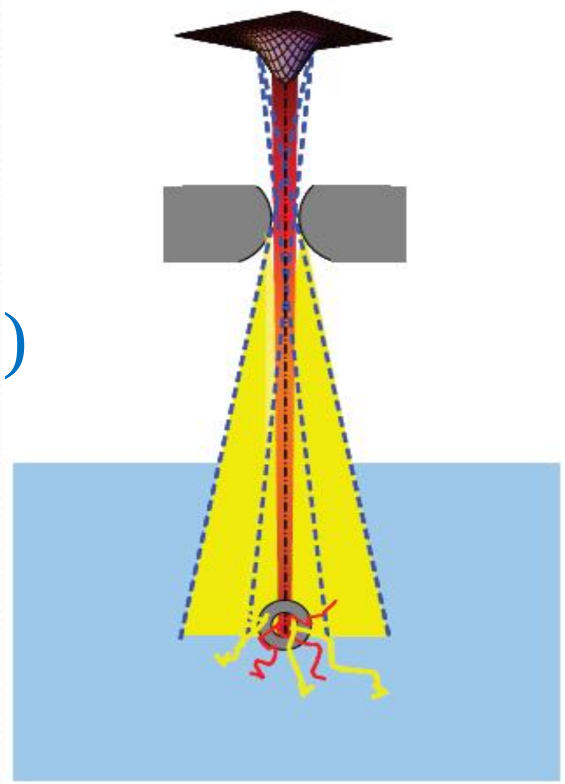
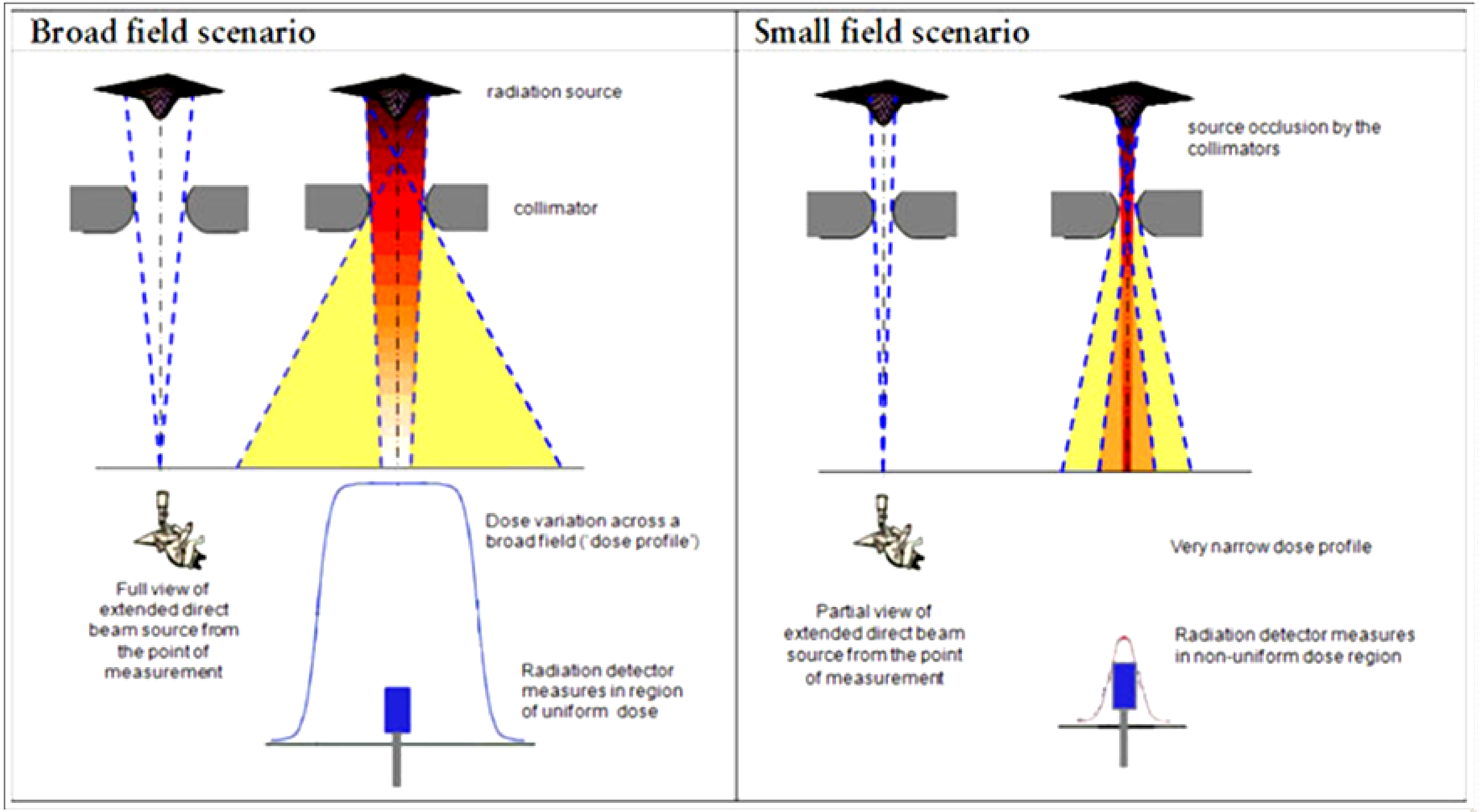
What is a small field?

- Beam related contributions
  - ➢ Loss of lateral charged particle equilibrium (III)
  - ➢ Partial occlusion of the primary source (I)



- Detector related contributions
  - ➢ Large size compared with beam dimensions (II)

Broad field versus small field



Left: In the broad field scenario, the extended beam source is fully visible from the position of measurement and the detector measures in a flat dose profile. Right: In the small field scenario, the extended beam source is occluded by the collimating device and the detector measures in a non-flat dose profile.

SITUATION IN LEKSELL GAMMA KNIFE

DOSIMETRY (NOW) AND BEFORE TRS IAEA 483

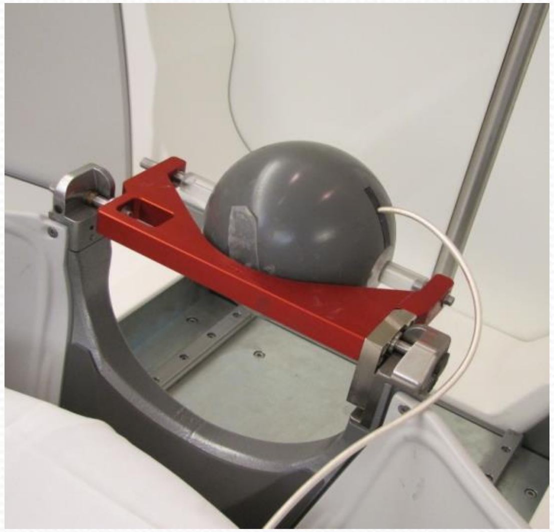
Leksell Gamma Knife dosimetry

- Reference dosimetry - calibration (dose rate measurement)
- Profiles for all collimators in X, Y, Z coordinates
- Relative collimator output factors
- Dosimetry audit, verification of complex dosimetry

Leksell Gamma Knife dosimetry

- Largest collimator size 16 mm (LGK Perfexion and Icon)
- Reference dosimetry - calibrated ion chamber at the unit center focus point
- Existing AAPM, IAEA or similar calibration protocols used
- Profiles measured by film dosimetry (especially Gafchromic)
- Relative output factors measured by various (stereotactic) detectors

ELEKTA ABS plastic spherical phantom



ELEKTA Dosimetry Phantom solid water spherical phantom

Current practice of small field dosimetry in gamma knife

- Existing calibration protocols IAEA TRS 277, AAPM TG21 and/or IAEA TRS 398, AAPM TG51 are very often still used with smaller or larger approximations

- New IAEA TRS 483 protocol for small field dosimetry is available since November 2017 and is being implemented in clinical practice in some departments

- Existing radiation detectors such as micro ion chambers, stereotactic diode detectors, scintillator detectors, microDiamond, film dosimetry (especially Gafchromic) and etc. are used together with Monte Carlo Calculations

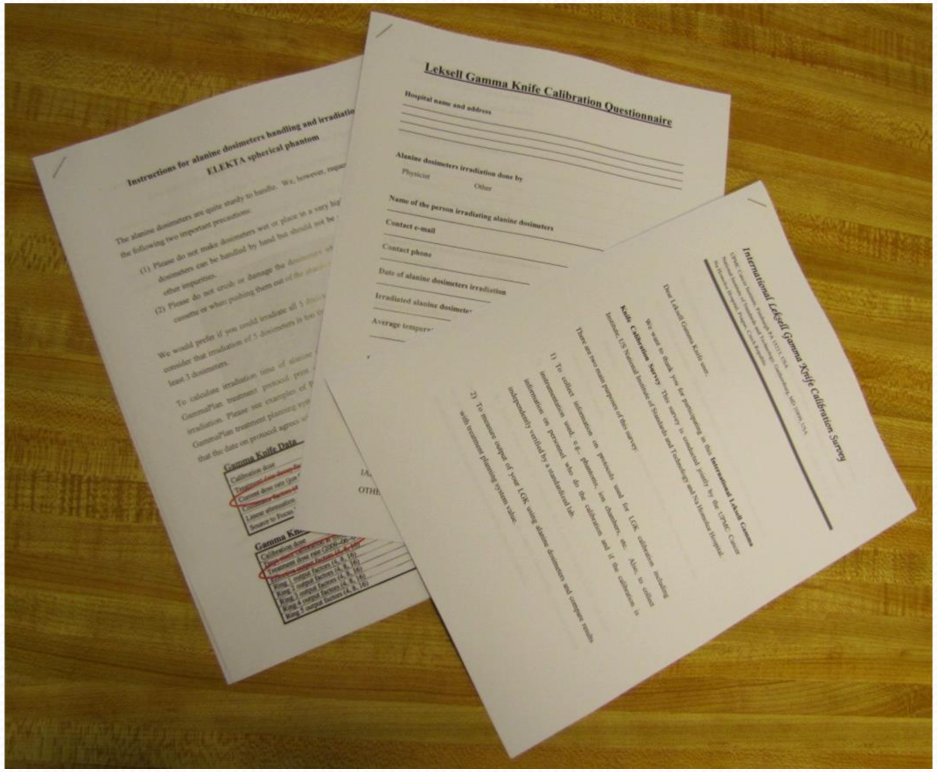
International Leksell Gamma Knife Calibration Survey (UPMC and NIST) years 2009 - 2012

- To collect information on calibration procedures including protocols, instrumentation (e.g. phantoms, ion chambers and etc.) used and other information related to calibration (e.g. independent verification of calibration, person responsible for calibration and etc.)

- To measure output of the Leksell Gamma Knife unit with alanine dosimetry and compare measured value with treatment planning system value

International Leksell Gamma Knife Calibration Survey

- Cover letter.
- Leksell Gamma Knife Calibration questionnaire.
- Instructions for alanine dosimeter handling and irradiation in the ELEKTA ABS spherical phantom.



Leksell Gamma Knife Calibration Questionnaire

Leksell Gamma Knife Model

☐ B ☐ C 1.1 or C 1.2 ☐ 4C ☐ Perfexion

Protocol used for calibration

☐ AAPM TG21 ☐ AAPM TG51 ☐ IAEA TRS 277 ☐ IAEA TRS 398 ☐ OTHER, please specify

Phantom used for calibration

☐ ELEKTA ABS plastic spherical phantom ELEKTA solid water spherical phantom ☐ OTHER, please specify

Ion chamber used for calibration

☐ Manufacturer ☐ Model ☐ Volume [cm^3] Last date of ion chamber calibration ☐ Calibration laboratory

Leksell Gamma Knife calibration performed by

☐ On-site physicist ☐ ELEKTA physicist ☐ Other, please specify ☐ Date of LGK calibration

Independent verification of calibration, please include result if available

☐ None ☐ RPC SRS audit ☐ IAEA TLD audit ☐ National TLD or ion chamber audit OTHER, please specify

Collimator relative output factors used

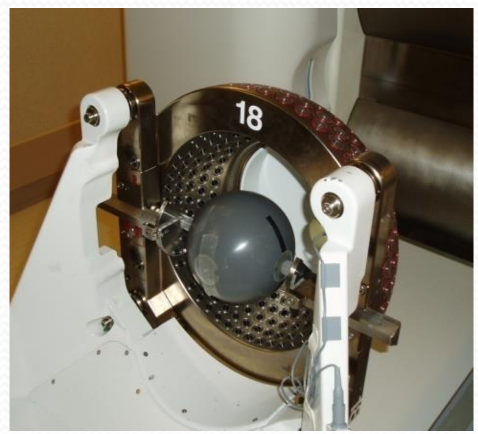
☐ ELEKTA default values ☐ Values measured by on-site physicist ☐ Other, please specify

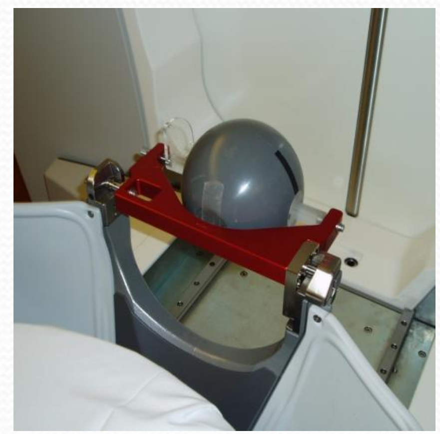
Alanine dosimeters irradiation

Gamma Knife Data

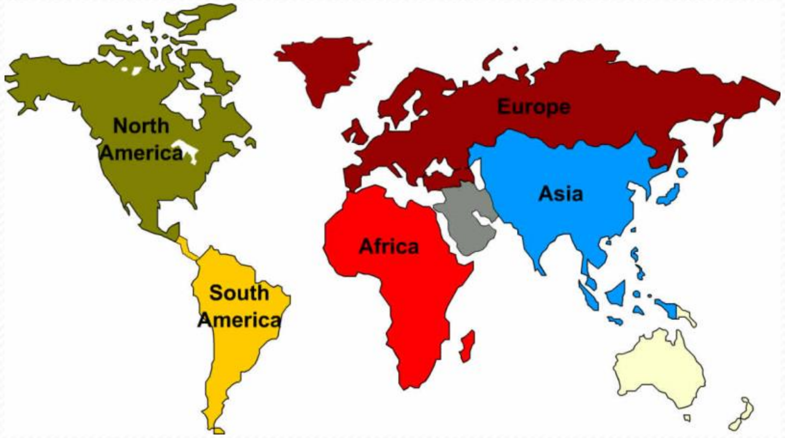
Calibration dose	3.633 Gy/min at 2007-09-20
Days since calibration at treatment date	623
Treatment dose rate (2009–06–04)	2.902 Gy/min
Effective output factors (4, 8, 16)	0.805 0.924 1
Ring 1 output factors (4, 8, 16)	0.799, 0.957, 0.961
Ring 2 output factors (4, 8, 16)	0.815, 0.946, 1.000
Ring 3 output factors (4, 8, 16)	0.792, 0.901, 0.986
Ring 4 output factors (4, 8, 16)	0.725, 0.808, 0.920
Ring 5 output factors (4, 8, 16)	0.663, 0.730, 0.851

Deliver 50.0 Gy





Participation in this project



- Total No. 99 LGK units surveyed
- Total No. 91 LGK centers
- Total No. 27 countries

North America	40
Asia	32
Europe	24
South America	1
Africa	1
Australia	1

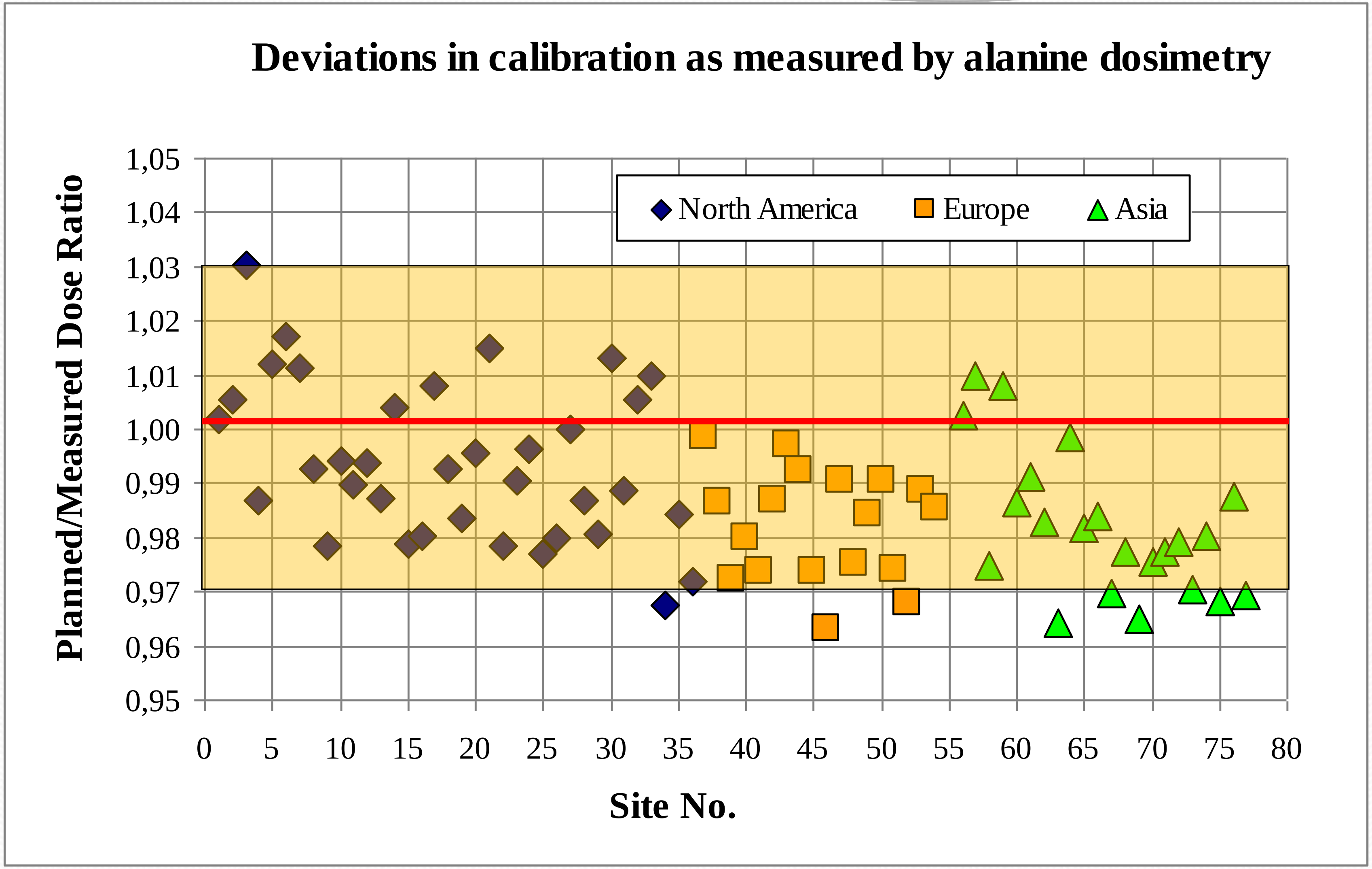
Calibration protocols used

• AAPM TG 21	26 (33 %)
• AAPM TG 51	8 (10 %)
• IAEA TRS 277	1 (1 %)
• IAEA TRS 398	35 (45 %)
• OTHER (NPL Code of Practice)	6 (8 %)
• OTHER (DIN 6800-2)	2 (3 %)

Ion chambers used for calibration

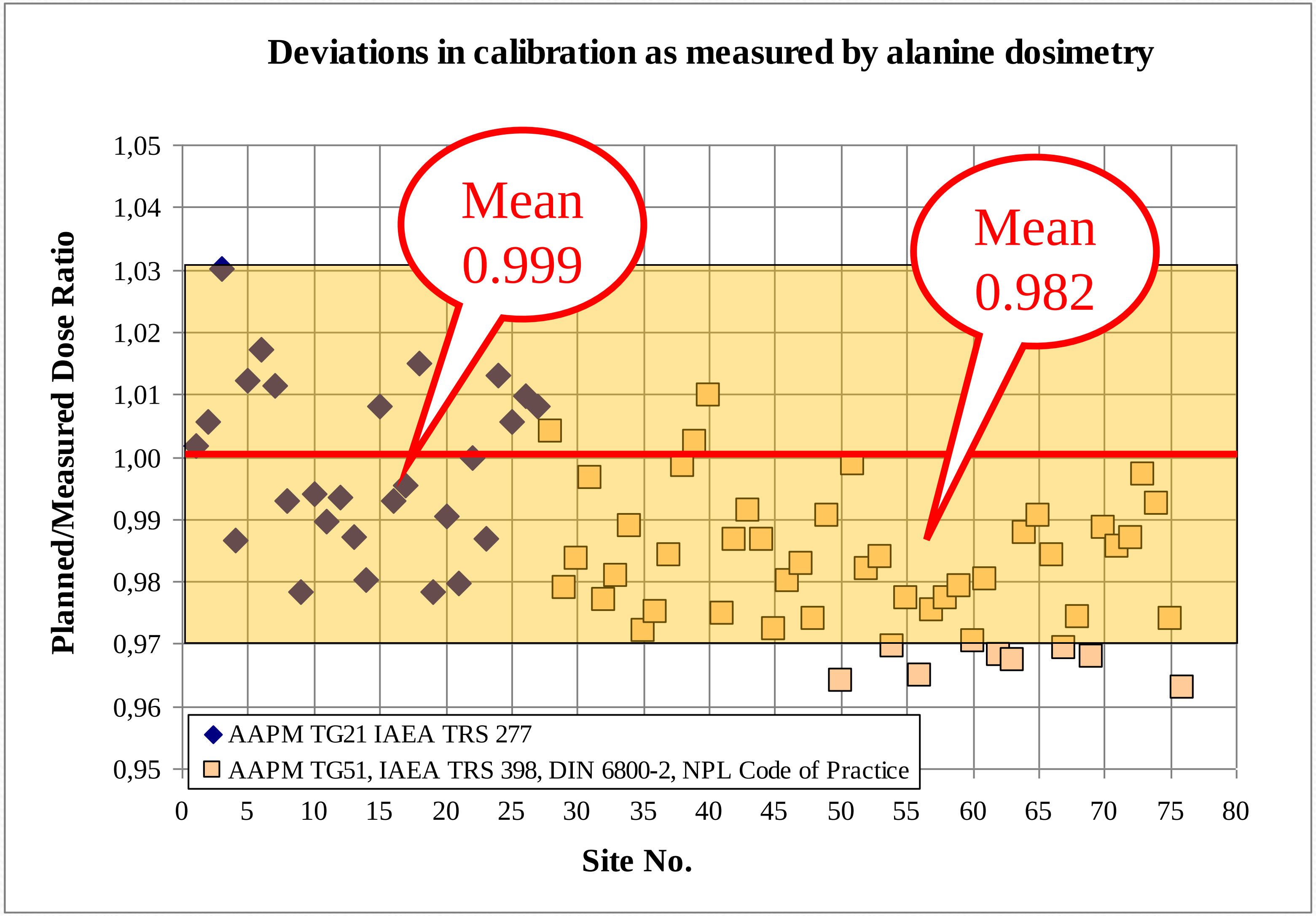
Ion chamber manufacturer and type	Ion chamber volume [cm^3]	Frequency in this study	
PTW 31010	0.125	32	41 %
Exradin A16	0.007	12	15 %
Capintec PR-05P	0.070	12	15 %
PTW 31002	0.125	8	10 %
PTW 31006	0.015	4	5 %
Exradin A1SL	0.057	4	5 %
Exradin A14SL	0.016	2	3 %
Wellhoffer IC-10	0.125	1	1 %
PTW 31016	0.016	1	1 %
Scanditronix RK-8305	0.120	1	1 %

Ratio of planned dose to alanine dosimetry measured dose



Plan/Measured Dose Ratio range 0.963 – 1.030

Ratio of planned dose to alanine dosimetry measured dose



Plan/Measured Dose Ratio range 0.963 – 1.030

Relative output factors used

- ELEKTA default values (MC calculated) 100 % sites

TRANSITION TO IAEA 483 ON LEKSELL GAMMA KNIFE:

REFERENCE DOSIEMTRY, RELATIVE DOSIMETRY

New small field formalism

Medical Physics Letter

A new formalism for reference dosimetry of small and nonstandard fields

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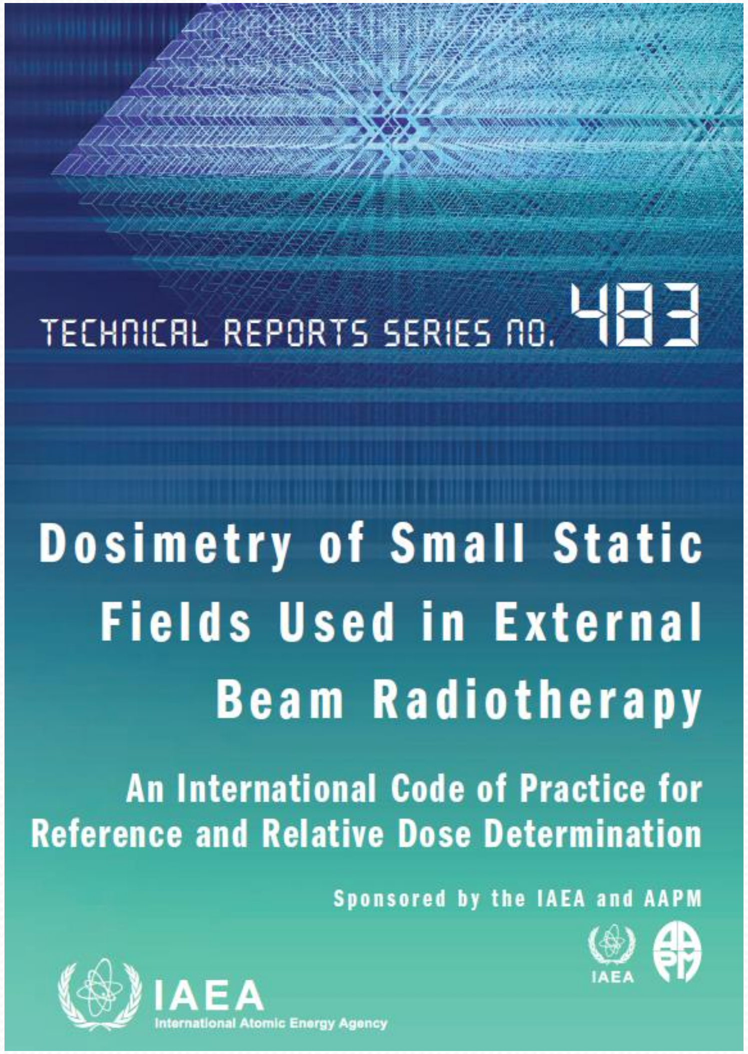


New small field formalism

- Modified reference conditions

- Two routes traceable to a broad beam calibration

1. Small static field dosimetry,which introduces an intermediate machine-specific-reference field (*msr*) for treatment machines that cannot establish a conventional reference field

2. Composite field dosimetry, which can include an intermediate machine-specific-reference field if needed, as well as a so-called plan-class specific reference field (*pcsr*)
   - The *pcsr* should be as close as possible to a class of clinical plans of interest, and provide a uniform dose over a region exceeding the dimensions of a reference detector

Small static fields – reference field

$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} \cdot N_{D,w,Q_0} \cdot k_{Q,Q_0} \cdot k_{Q_{msr},Q}^{f_{msr},f_{ref}}$$

$k_{Q_{msr},Q}^{f_{msr},f_{ref}}$ is a factor which corrects for the differences between the conditions of field size, geometry, phantom material and beam quality of the conventional reference field f_{ref} and the machine-specific reference field f_{msr}

$$k_{Q_{msr},Q}^{f_{msr},f_{ref}} = \frac{D_{w,Q_{msr}}^{f_{msr}} / M_{Q_{msr}}^{f_{msr}}}{D_{w,Q}^{f_{ref}} / M_{Q}^{f_{ref}}}$$

Small static fields – clinical field

$$D_{w,Q_{clin}}^{f_{clin}} = D_{w,Q_{msr}}^{f_{msr}} \cdot \Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$$

$\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ is a field factor which converts the absorbed dose to water for the machine-specific reference field, f_{msr} to the absorbed dose to water for the clinical field f_{clin}. In relative dosimetry of single static fields this factor is conventionally called a field output factor, which ought to be defined as a ratio of D_w.

It can be calculated directly as a ratio of D_w using Monte Carlo alone or it can be measured as a ratio of detector readings multiplied by a Monte Carlo calculated correction factor.

$$\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = \frac{M_{Q_{clin}}^{f_{clin}}}{M_{Q_{msr}}^{f_{msr}}} \cdot k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$$

Small static fields

1

REFERENCE DOSIMETRY

$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} \, N_{D,w,Q_0} \, k_{Q,Q_0} \, k_{Q_{msr},Q}^{f_{msr},f_{ref}}$$

Broad beam reference field f_{ref}

$N_{D,w,Q_0} \quad k_{Q,Q_0}$

Hypothetical reference field f_{ref}

$k_{Q_{msr},Q}^{f_{msr},f_{ref}}$

Machine specific reference field f_{msr}

Radiosurgical collimators
∅ as low as 1.8cm

BrainLAB
micro MLC
10cm x 10cm

CyberKnife
∅ 6.0 cm

GammaKnife
∅ 1.6/1.8 cm

TomoTherapy
5cm x 20cm

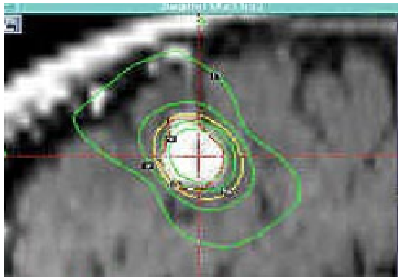
● ≡ Ionization chamber

RELATIVE DOSIMETRY

$$D_{w,Q_{clin}}^{f_{clin}} = D_{w,Q_{msr}}^{f_{msr}} \, \Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$$

$\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$

Clinical f_{clin}



e.g. a GammaKnife clinical plan

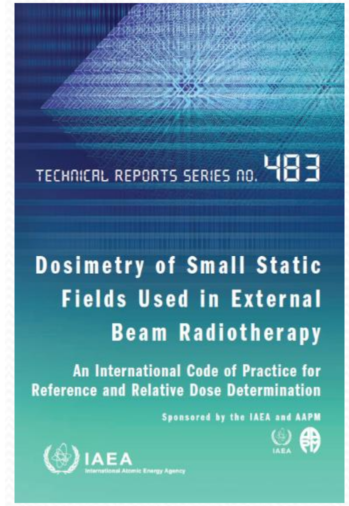
Leksell Gamma Knife® Icon™ reference dosimetry

- REFERENCE DOSIMETRY

$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} \, N_{D,w,Q_0}^{f_{ref}} \, k_{Q_{msr},Q_0}^{f_{msr},f_{ref}}$$

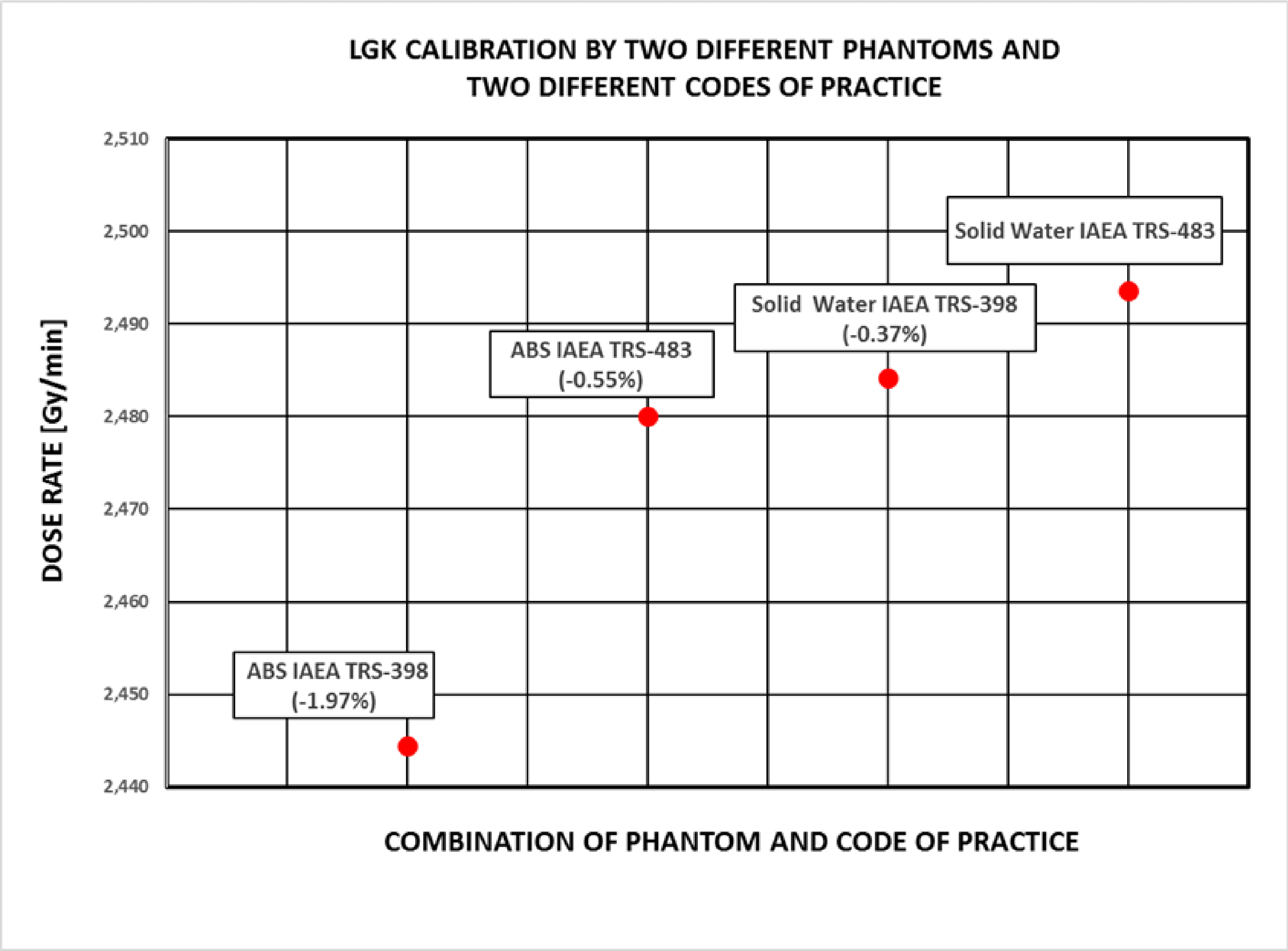
TABLE 14. CORRECTION FACTORS $k_{Q_{msr},Q_0}^{f_{msr},f_{ref}}$ FOR THE GAMMA KNIFE MODELS PERFEXION AND 4C [110, 153]

Chamber type	Perfexion f_{msr} = 16 mm ∅			4C f_{msr} = 18 mm ∅		
	Solid Water	ABS	Water	Solid Water	ABS	Water
PTW T31010	1.0037	1.0146	1.0001	0.9958	0.9990	0.9924
PTW T31016	1.0040	1.0110	0.9991	1.0014	1.0025	0.9964
Exradin A1SL	1.0046	1.0138	1.0006	1.0009	1.0014	0.9967
Exradin A14SL	1.0154	1.0194	1.0112	1.0116	1.0060	1.0058
Exradin A16	1.0167	1.0295	1.0127	1.0163	1.0217	1.0104
IBA CC01	1.0213	1.0292	1.0169	1.0203	1.0208	1.0157
IBA CC04	1.0107	1.0117	1.0062	1.0086	1.0049	1.0040
Capintec PR05-P 4.7	1.0059	1.0070	1.0010	1.0007	0.9960	0.9951
Capintec PR05-P 7.6	1.0025	1.0126	0.9976	0.9885	0.9972	0.9844



Leksell Gamma Knife® Icon™ reference dosimetry comparison

→ Change in existing IAEA TRS 398 calibration in treatment planning system by 1.44%



Leksell Gamma Knife® Icon™ relative dosimetry

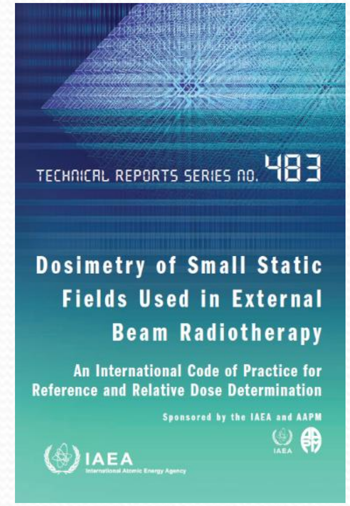
- RELATIVE DOSIMETRY - OF

$$\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = \frac{M_{Q_{clin}}^{f_{clin}}}{M_{Q_{msr}}^{f_{msr}}} k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$$

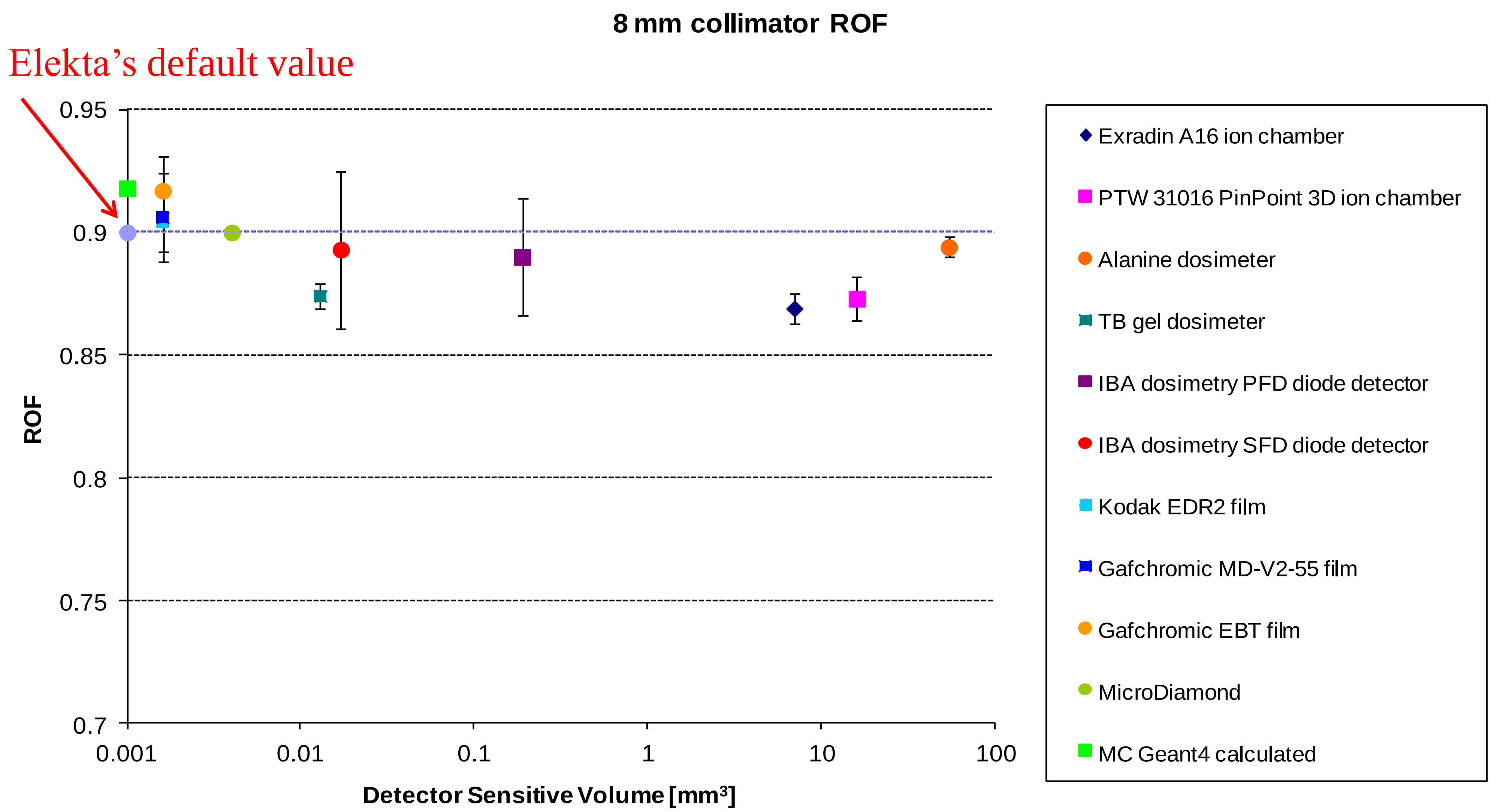
TABLE 25. FIELD OUTPUT CORRECTION FACTORS $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ FOR THE GAMMA KNIFE MODEL PERFEXION, AS A FUNCTION OF THE DIAMETER OF THE CIRCULAR COLLIMATOR [179]

Model	Type	4 mm Ø	8 mm Ø	16 mm Ø
PTW T31006	Ionization chamber	—[a]	1.025	1.000
PTW T31014	Ionization chamber	—[a]	1.030	1.000
PTW T31015	Ionization chamber	—[a]	—[a]	1.000
PTW T31016	Ionization chamber (PinPoint 3D)	—[a]	1.032	1.000
PTW T60008	Diode (photon/shielded)	0.951	0.971	1.000
PTW T60012	Diode (electron/unshielded)	0.965	0.996	1.000
PTW T60016	Diode (photon/shielded)	0.958	0.981	1.000
PTW T60017	Diode (electron/unshielded)	0.961	0.997	1.000
PTW T60003	Diamond detector (natural)	—[a]	1.006	1.000
PTW T60019	Diamond detector (synthetic)	0.993	1.005	1.000

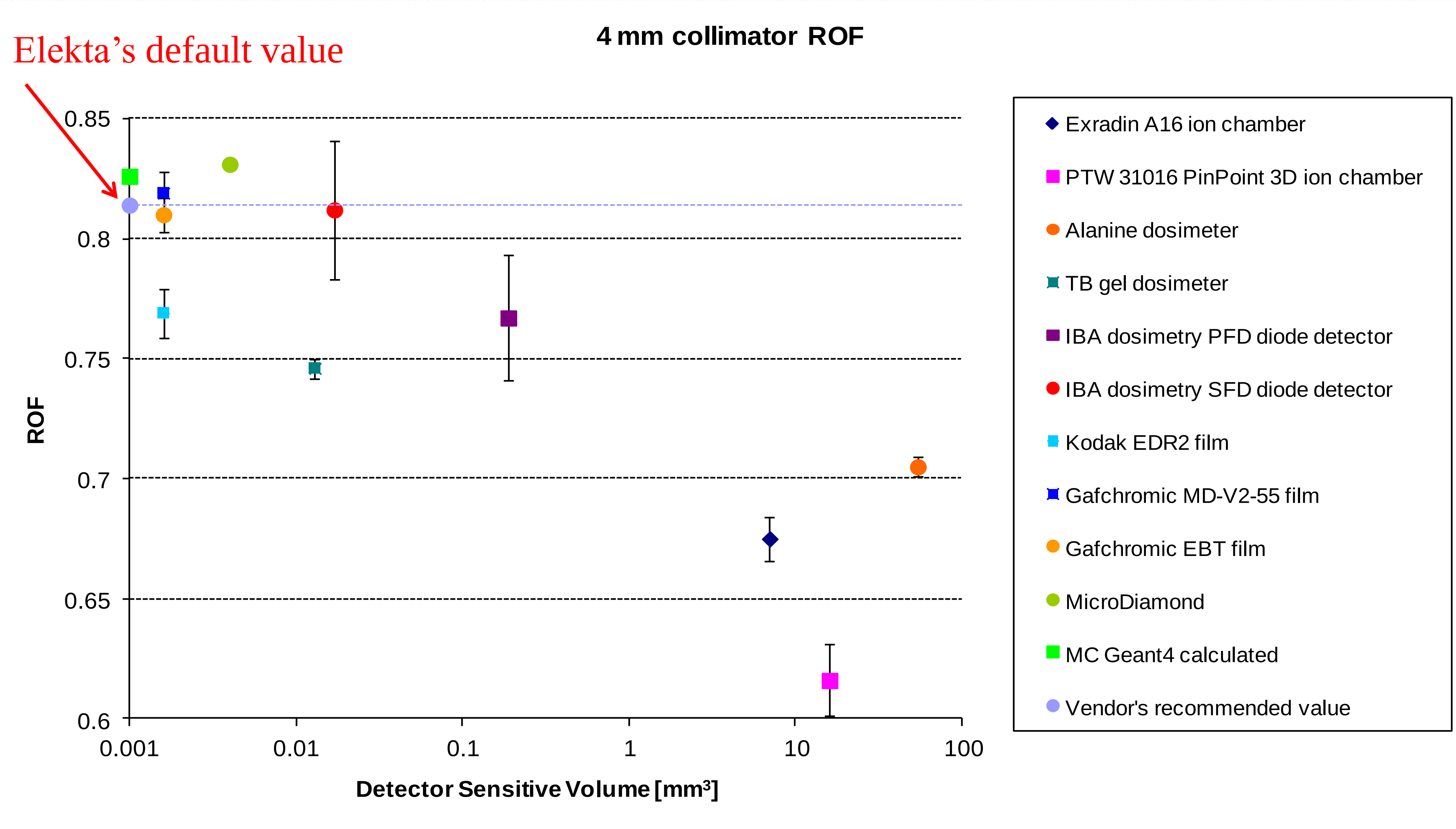
[a] A large correction factor makes this chamber unsuitable for output measurements with this collimator.



Relative output factor for 8 mm collimator



Relative output factor for 4 mm collimator



Relative output factors for 8 a 4 mm summary (not corrected for IAEA TRS 483)

Detector	Measured 4 mm ROF	Measured 8 mm ROF	Deviation to vendor's values [%]	
			4 mm ROF	8 mm ROF
ELEKTA value	**0,814**	**0,900**		
Exradin A16 ion chamber	0,675 ± 0,009	0,869 ± 0,006	-17,1	-3,4
PTW 31016 PinPoint 3D ion chamber	0,616 ± 0,015	0,873 ± 0,009	-24,3	-3,0
Alanine dosimeter	0,705 ± 0,004	0,894 ± 0,004	-13,4	-0,7
TB gel dosimeter	0,746 ± 0,004	0,874 ± 0,005	-8,4	-2,9
IBA dosimetry PFD diode detector	0,767 ± 0,026	0,890 ± 0,024	-5,8	-1,1
IBA dosimetry SFD diode detector	0,812 ± 0,029	0,893 ± 0,032	-0,2	-0,8
Kodak EDR2 film	0,769 ± 0,010	0,904 ± 0,012	-5,5	0,4
Gafchromic MD-V2-55 film	0,819 ± 0,009	0,906 ± 0,018	0,6	0,7
Gafchromic EBT film	0,810 ± 0,007	0,917 ± 0,014	-0,5	1,9
MC Geant4 calculated	0,826 ± 0,006	0,918 ± 0,004	1,5	2,0
MicroDiamond	0,831 ± 0,001	0,900 ± 0,001	2,1	-0,1

Relative output factors (OF) for 8 and 4 mm summary

- Maximum deviation in experimental data measured by MicroDiamond to Monte-Carlo calculated vendor default values 1.4 % after IAEA TRS 483

8 mm OF measured in ABS phantom		**4 mm OF measured in** ABS phantom		**8 mm OF measured in** Solid Water phantom		**4 mm OF measured in** Solid Water phantom	
TRS 398	TRS 483	TRS 398	TRS 483	TRS 398	TRS 483	TRS 398	TRS 483
-0.1 %	0.6 %	2.1 %	1.4 %	-1.5 %	-1.0 %	2.1 %	1.4 %

Conclusions – gamma knife dosimetry transition to TRS 483

- Re-calibration of LGK Icon was made based on TRS 483 protocol which better reflects small field dosimetry conditions.

- Relatively small (within 2%) deviations to existing calibration and default Output factors values were observed.

- Critical aspect for these kind of measurements is a proper choice of detector for both absolute and relative dosimetry. In our measurements PTW 31010 ion chamber and PTW 60019 microDiamond detector were used.

DOSIMETRY AUDIT

Dosimetry audit

How to protect:

- Patients
- Department and hospital reputation
- Your medical physics practice

→ **Dosimetry audits!**

Dosimetry audits after LGK Co-60 reloading

- On-site audit: performed by National Radiation Protection Institute, Prague, Czech Republic

SÚRO Státní ústav radiační ochrany, v. v. i.
National Radiation Protection Institute

- Postal audit: MD Anderson Cancer Center, The MD Anderson Dosimetry Laboratory, Houston, TX, USA

THE UNIVERSITY OF TEXAS MD Anderson ~~Cancer~~ Center Making Cancer History® The MD Anderson Dosimetry Laboratory

Dosimetry audit performed by National Radiation Protection Institute, Prague, Czech Republic

Státní ústav radiační ochrany, v. v. i.
National Radiation Protection Institute

- Dose rate measured in Elekta spherical ABS plastic phantom by PTW 31010 ion chamber and PTW Unidos electrometer.
- Mean doses measured in anthropomorphic head phantom (adapted Alderson Radiation therapy phantom, RSD, CA, USA) for a clinical test plan calculated by both Leksell GammaPlan algorithms TMR10 and Convolution. Two PTW 31010 ion chambers and PTW Unidos electrometers were used for a measurement.
- Gafchromic EBT3 film measurement for TMR10 algorithm was done. Epson V750 film scanner used. Software OmniPro I'mRT was used for gamma analysis.

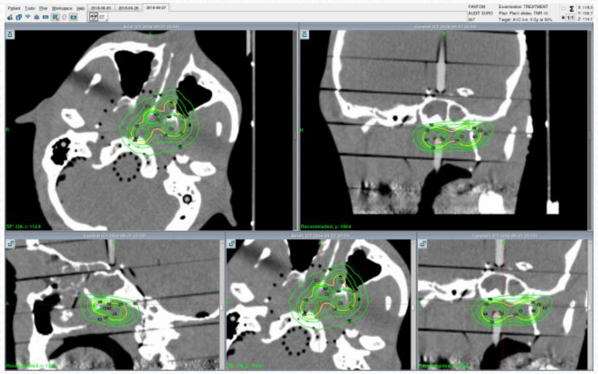
Phantoms setup and treatment planning

Státní ústav radiační ochrany, v. v. i.
National Radiation Protection Institute

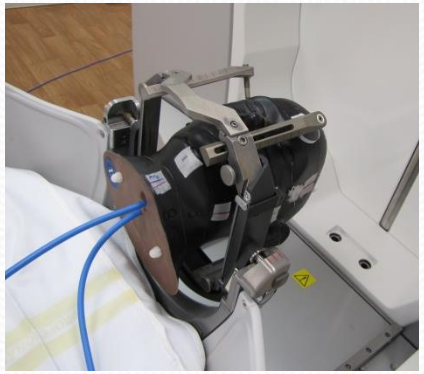
- ABS plastic Elekta spherical phantom (six measurements in two different ion chamber setups)

- Anthropomorphic head phantom with dosimetry film and two ion chambers

Stereotactic CT imaging



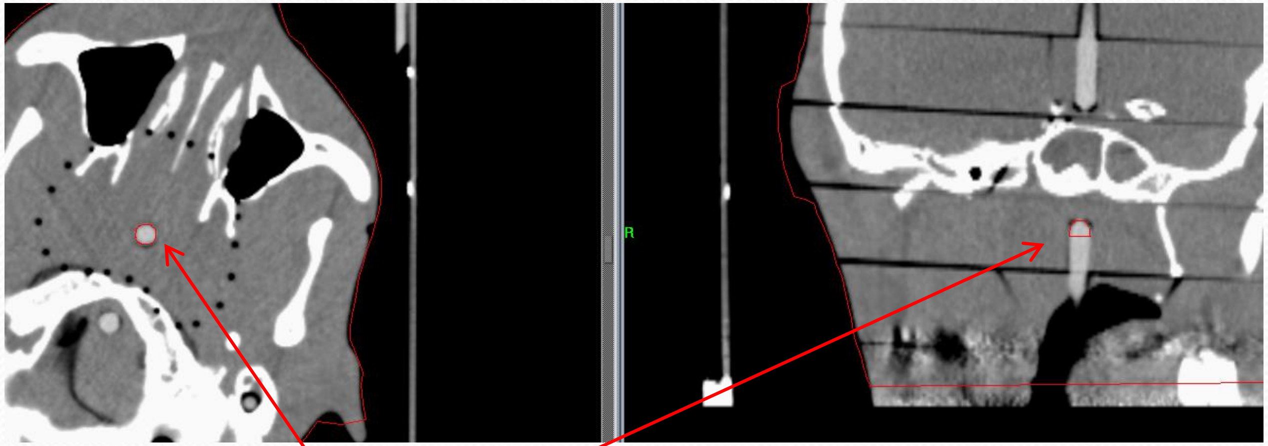
Treatment planning



Dose delivery

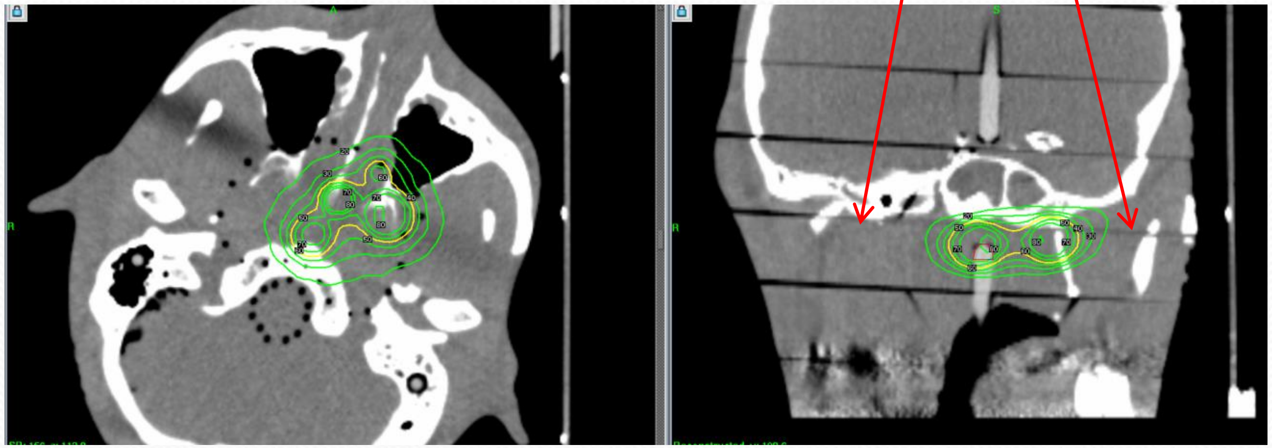
Treatment planning

- Anthropomorphic head phantom with dosimetry film and two ion chambers



Ion chamber sensitive volume countored within the accuracy better than 2 %.

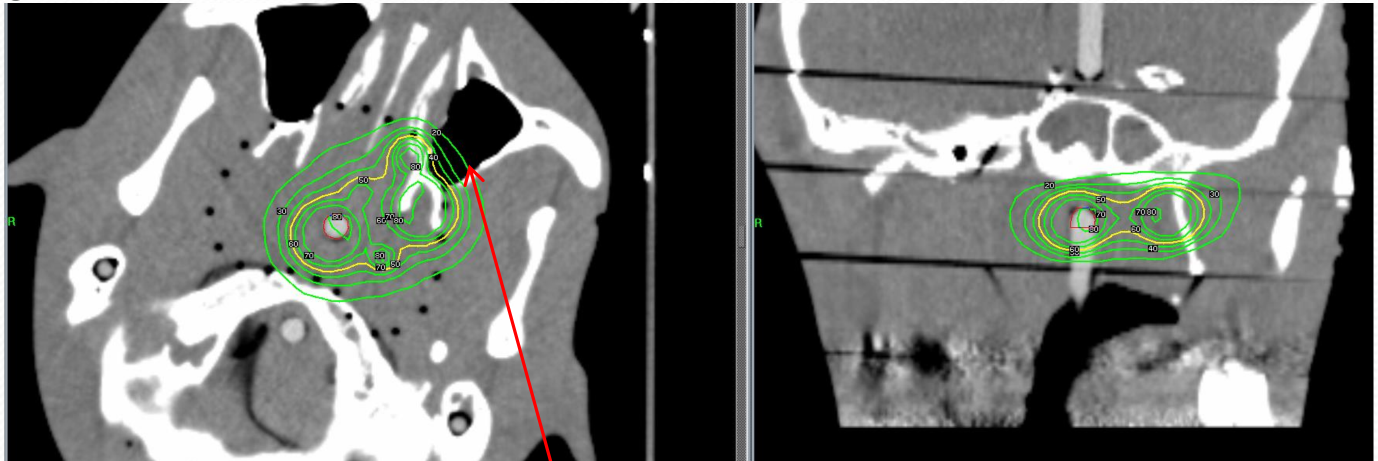
EBT3 Gafchromic film position



Treatment planning

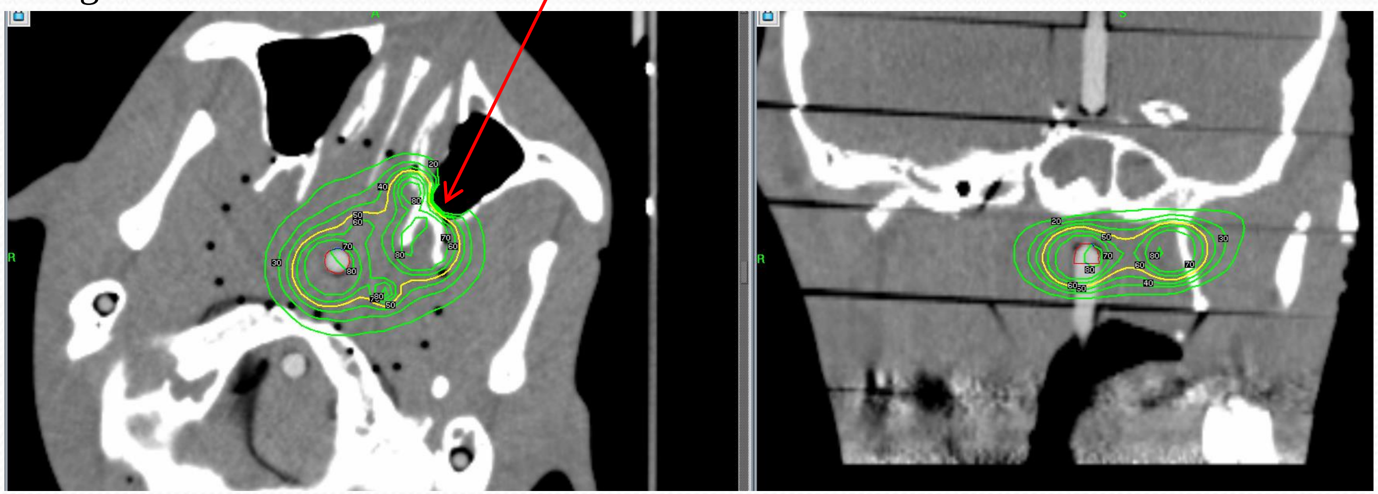
- Anthropomorphic head phantom with dosimetry film and two ion chambers

TMR10 calculation algorithm



Difference between TMR10 and Convolution algorithms

Convolution calculation algorithm



Dosimetry audit results

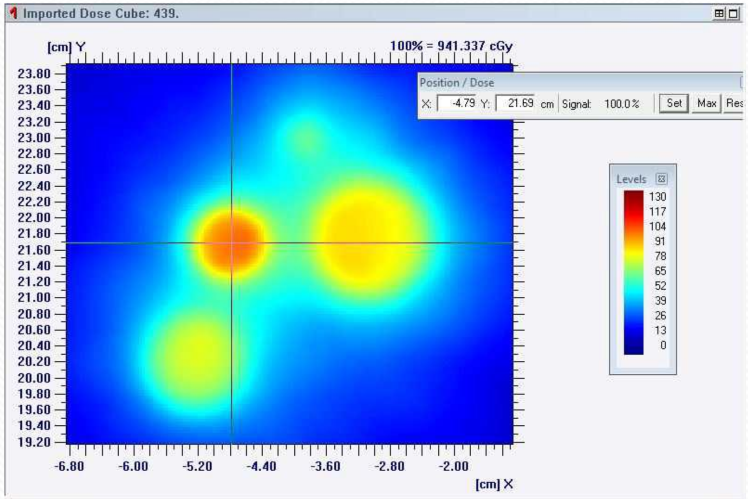
Verified parameter	Measured value	Reported value	Deviation	Tolerance
Dose rate in the ABS phantom	3.655 Gy/min	3.631 Gy/min	0.7%	±2%
Mean dose in target volume for TMR10 algorithm	8.014 Gy	8.100 Gy	-1.1%	±3%
Mean dose in target volume for Convolution algorithm	8.196 Gy	8.000 Gy	2.5%	±3%
Gamma analysis for film and TMR10 algorithm (4%/3mm)	98.5%	N.A.	N.A.	≥ 95%

$$\Delta\ [\%] = 100*(M_{measured} - M_{reported})/M_{reported}$$

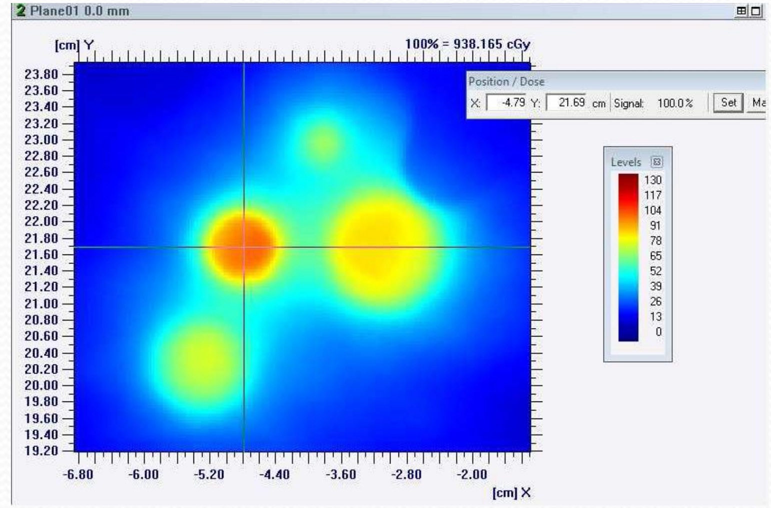
Dosimetry audit results

Státní ústav radiační ochrany, v. v. i.
National Radiation Protection Institute

Leksell GammaPlan TMR10 calculated dose distribution



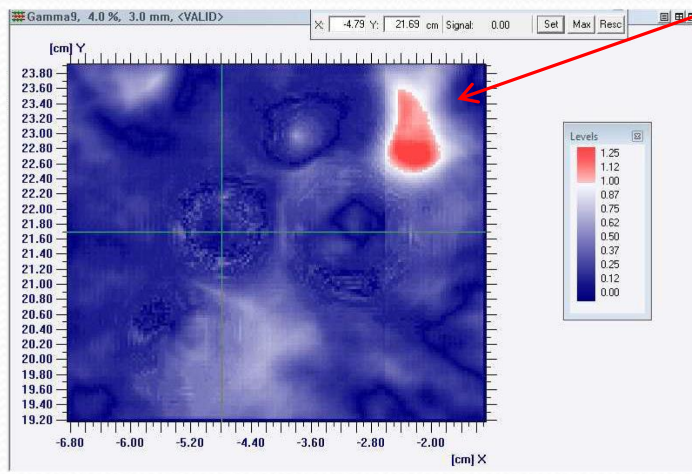
EBT3 Gafchromic film measured dose distribution

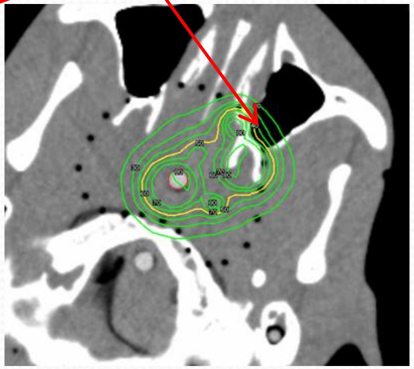


Comparison of dose profiles

Results of gamma analysis

Not passing





Dosimetry audit performed by the MD Anderson Dosimetry Laboratory

- Mean doses measured in stereotactic radiosurgery head phantom in two TLDs.
- Gafchromic EBT3 film measurement for TMR10 algorithm was done.

The MD Anderson Dosimetry Laboratory audit

The MD Anderson Dosimetry Laboratory

- Assess accuracy of the entire process:

  - CT/MRI scan
  - Contouring
  - Dose calculation
  - Radiation delivery

Stereotactic Radiosurgery Head Phantom

- Plastic head filled by water

The MD Anderson Dosimetry Laboratory audit

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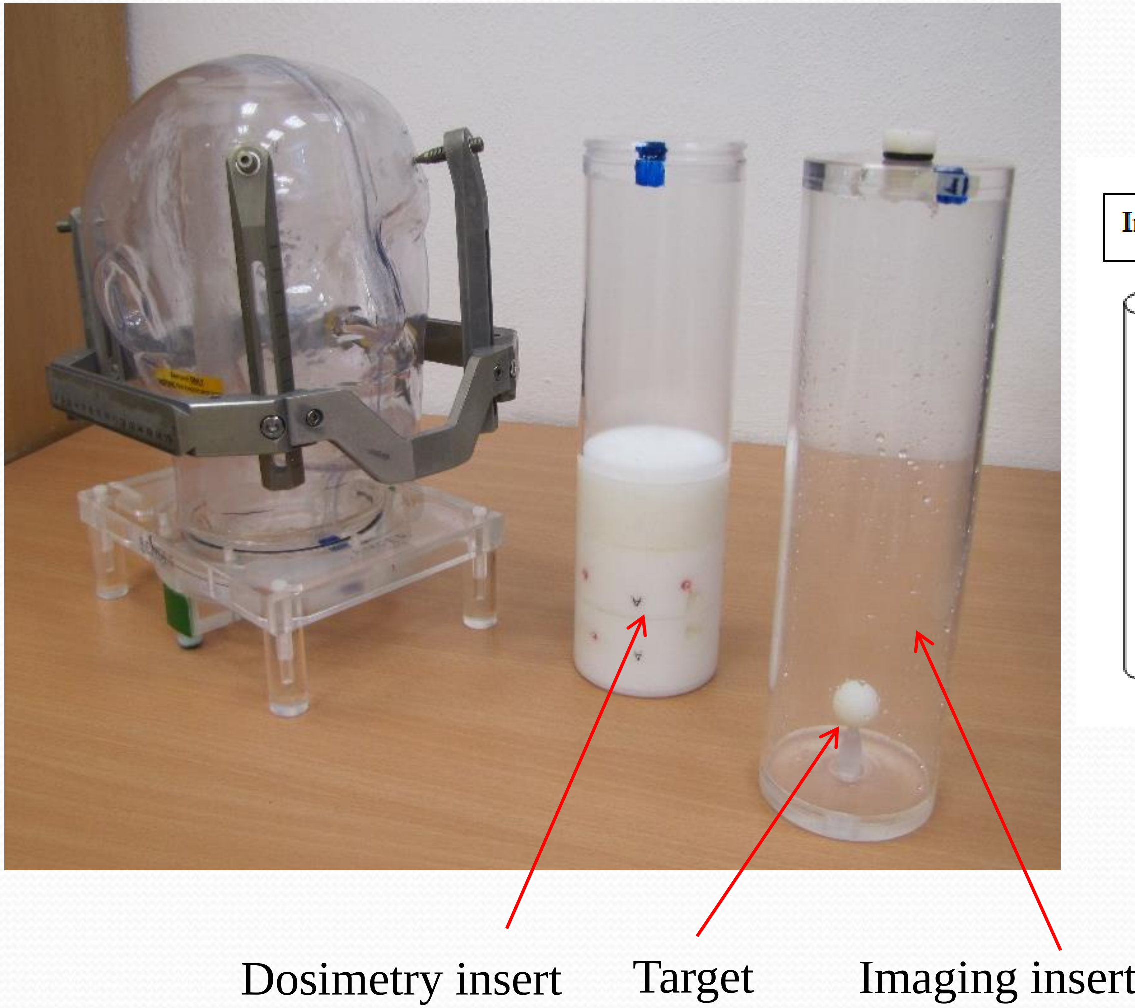
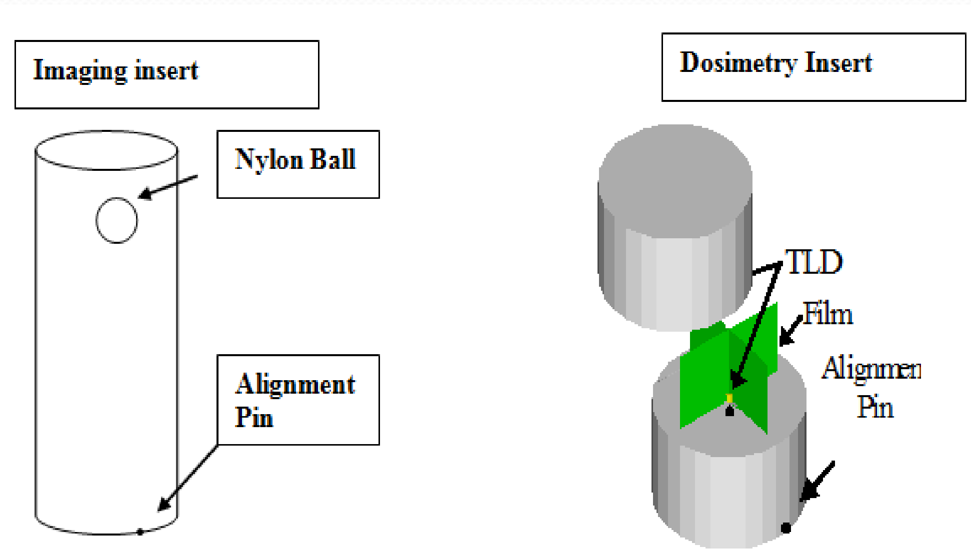
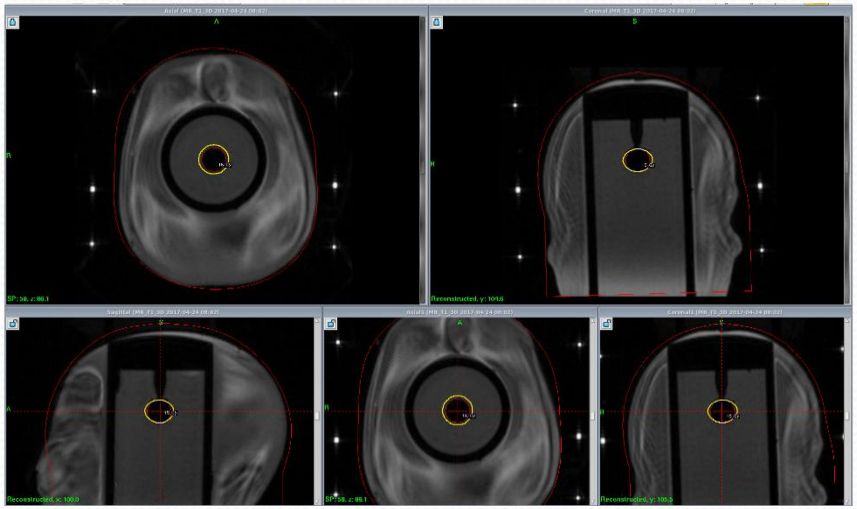


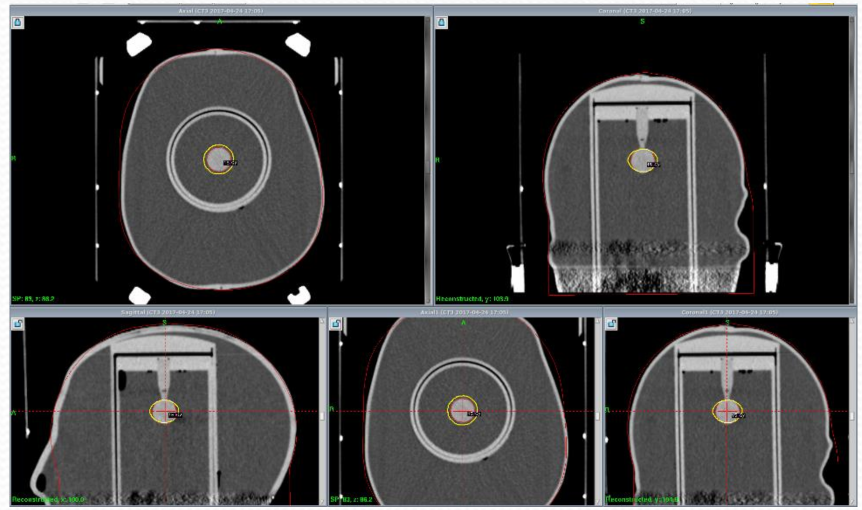


Treatment planning

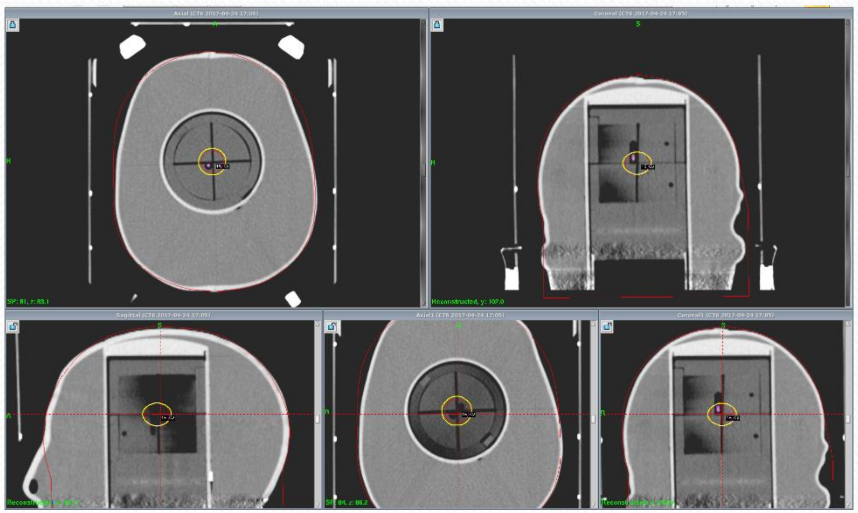
Imaging insert MR



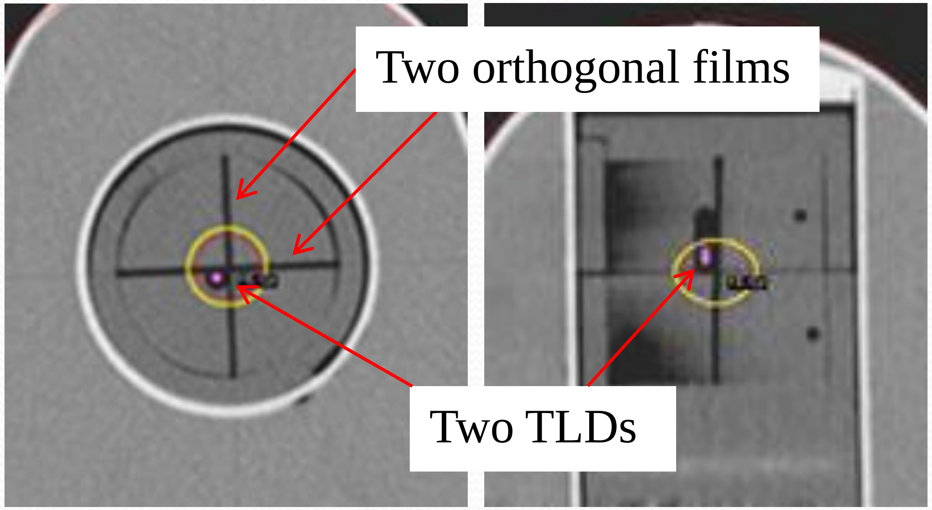
Imaging insert CT



Dosimetry insert CT



Dosimetry insert CT – TLD detail



Dosimetry audit results

The MD Anderson Dosimetry Laboratory

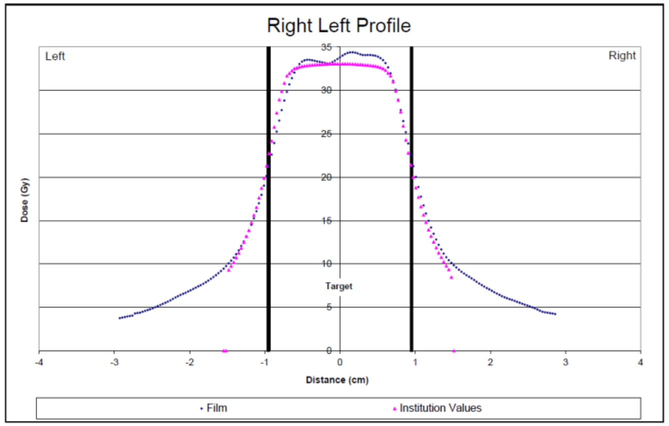
Verified parameter	Measured value	Reported value	Deviation	Tolerance
Dose to upper TLD capsule	31.59 Gy	31.70 Gy	0.997	0.95 -1.05
Dose to lower TLD capsule	33.32 Gy	32.00 Gy	1.041	0.95 -1.05
Gamma analysis for coronal film (5%/3mm)	97%	N.A.	N.A.	≥ 85%
Gamma analysis for sagittal film (5%/3mm)	94%	N.A.	N.A.	≥ 85%

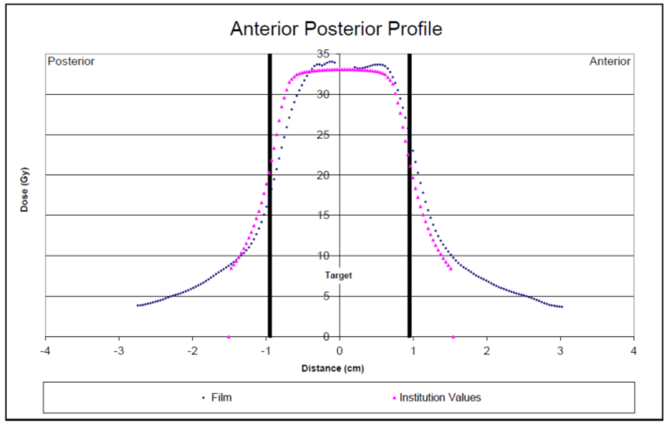
$$\Delta = M_{measured}/M_{reported}$$

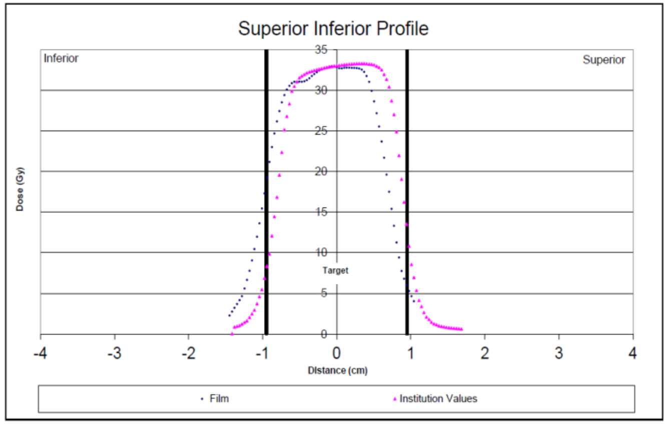
Dosimetry audit results

The MD Anderson Dosimetry Laboratory

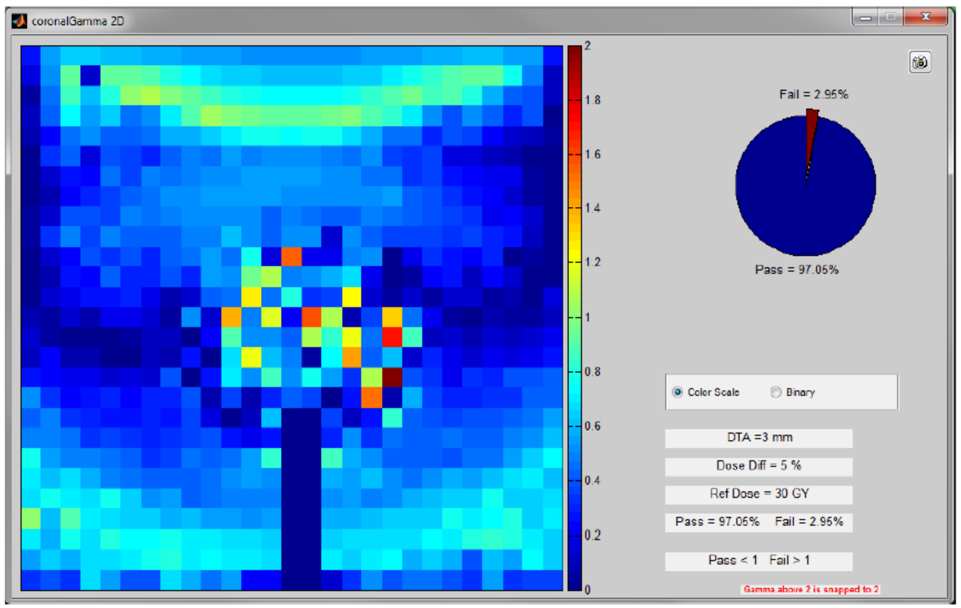
Comparison of dose profiles



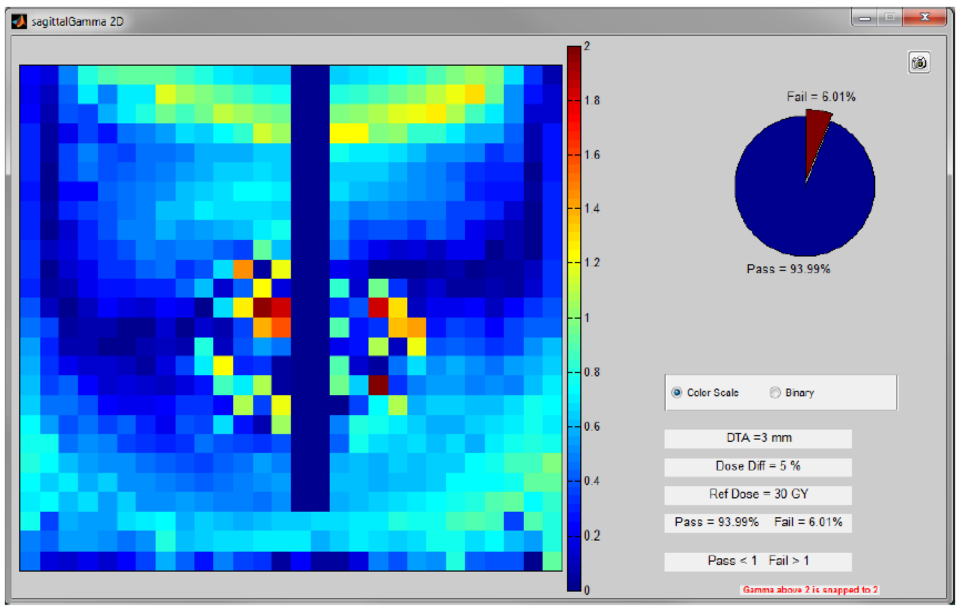




Results of gamma analysis for coronal film



Results of gamma analysis for sagittal film



CONCLUSIONS AND SUMMARY

General conclusions and summary

- New IAEA TRS 483 protocol for small field dosimetry is available since November 2017 and is being slowly implemented in gamma knife clinical practice.

- The development, characterization and implementation in clinical dosimetry of new small detectors e.g. diode detectors, microdiamond, scintillation detectors, small TLD and alanine pellets, micro liquid ion chamber and etc. is ongoing.

- Mandatory dosimetry audits (law, users, vendors)

- Special education and training in small field dosimetry

Thank you for your attention!