High Dose, Small Field Radiation Therapy: Lessons from the HyTEC Project and the ICRU 91 Report

Part 1: Small Field Dosimetry

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McGill

Disclosures

- My work is supported in part by the Canadian Institutes of Health Research, the Natural Sciences and Engineering Research Council, Canada through operating grants and training grants.
- I am working with Sun Nuclear Corporation and Lifeline Software Inc on technology commercialization projects
- I am working with RefleXion Medical on a small field dosimetry project
- Some brand names of commercial products are mentioned in this presentation. This does not represent any endorsement of one product or manufacturer over another

NSERC CRSNG

Medical Physics
RESEARCH TRAINING NETWORK

CIHR IRSC

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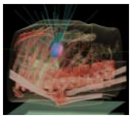
In ICRU91: SRT = {SBRT/SABR, SRS}



- **Reference** frame (physical or imaging only)
- **Precision** < 1 mm (real time tracking, repositioning)
- Multiple **SMALL** beams (non coplanar)
- Specific dose distribution (+ MC ?)
- Limited target volume = **High dose (> 5 Gy)/few fractions (1, 5, 10, …)**

- SBRT: B = body, fractionated?
- SABR: A= Ablative: not always, dose per fraction, different biology?
- SRS: RS= radiosurgery: single fraction, brain only?

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Why ICRU?

- Need for a common language
  - Within the department of radiation oncology
  - Within the hospital between health professionals
  - Between institutions locally and internationally
- Importance of harmonizing prescribing, recording and reporting
  - Is the prescription volume the same from one institution to another
  - Is the prescribed dose delivered in a homogeneous and identical manner between one clinic and another?
  - What is dose homogeneity?
  - What are the parameters describing the treatment?

A technology driven field


CyberKnife


C-arm SRT accelerator


TomoTherapy

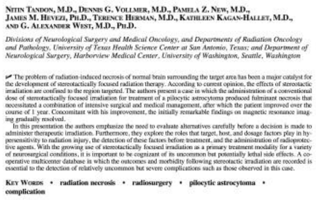

Vero


GammaKnife

Radiation fields are small and the dose per fraction is high!!

Volumetric precision

J. Neurosurg 95: 507-512, 2001



Nitin Tandon, M.D., Dennis G. Vollmer, M.D., Pamela Z. New, M.D., James M. Hevezi, Ph.D., Terence Herman, M.D., Kathleen Kagan-Hallet, M.D., and G. Alexander West, M.D., Ph.D.

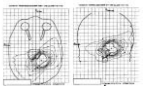
Divisions of Neurological Surgery and Medical Oncology, and Departments of Radiation Oncology and Pathology, University of Texas Health Science Center at San Antonio, Texas; and Department of Neurological Surgery, Harborview Medical Center, University of Washington, Seattle, Washington

The problem of radiation-induced necrosis of normal brain surrounding the target area has been a major catalyst for the development of stereotactically focused radiation therapy. According to current opinion, the effects of stereotactic irradiation are confined to the region targeted. The authors present a case in which the administration of a conventional dose of stereotactically focused irradiation for treatment of a pilocytic astrocytoma produced fulminant necrosis that necessitated a combination of intensive surgical and medical management, after which the patient improved over the course of 1 year. Concomitant with his improvement, the initially remarkable findings on magnetic resonance imaging gradually resolved.

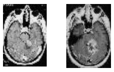
In this presentation the authors emphasize the need to evaluate alternatives carefully before a decision is made to administer therapeutic irradiation. Furthermore, they explore the roles that target, host, and dosage factors play in hypersensitivity to radiation injury, the detection of these factors before treatment, and the administration of radioprotective agents. With the growing use of stereotactically focused irradiation as a primary treatment modality for a variety of neurosurgical conditions, it is important to be cognizant of its uncommon but potentially lethal side effects. A cooperative multicenter database in which the outcomes and morbidity following stereotactic irradiation are recorded is essential to the detection of relatively uncommon but severe complications such as those observed in this case.

Key Words • **radiation necrosis** • **radiosurgery** • **pilocytic astrocytoma** • **complication**

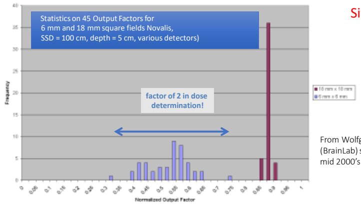
D_{100} = 18.4 Gy
D_{80} = 14.4 Gy
V_{16Gy} = 17.2 cm^3



T1 weighed


pre
8 months post

Measured Output Factors among users / machines



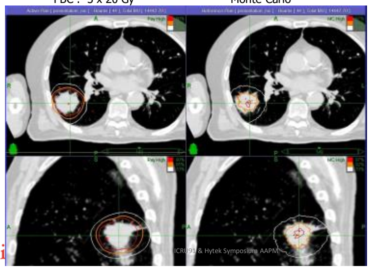
Situation in the mid-2000's!

From Wolfgang Ullrich (BrainLab) situation in mid 2000's

New-generation dose calculation algorithms

PBC : 3 x 20 Gy

Monte-Carlo

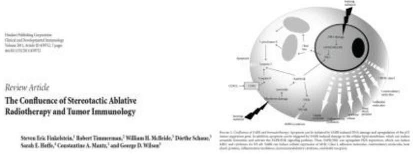


— **63.5** Gy
— **60.0** Gy
— **50.0** Gy

Radioresistant tumours

- Biology of high dose / fraction : **BED > 100 Gy**

- Melanoma
- Renal tumours
- Sarcomas
- …

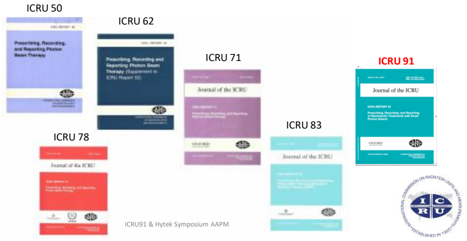


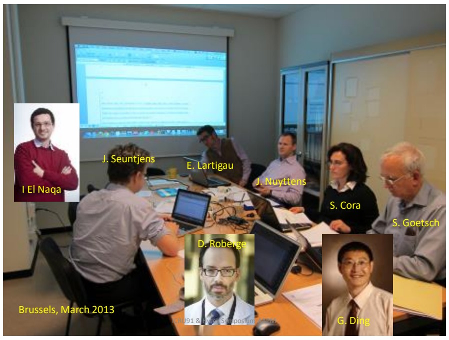
Review Article

The Confluence of Stereotactic Ablative Radiotherapy and Tumor Immunology

Steven Eric Finkelstein,[1] Robert Timmerman,[2] William H. McBride,[3] Dörthe Schaue,[3] Sarah E. Hoffe,[4] Constantine A. Mantz,[1] and George D. Wilson[5]

ICRU Reports on Prescribing, Recording & Reporting of EBRT





ICRU Report 91 - Table of Contents

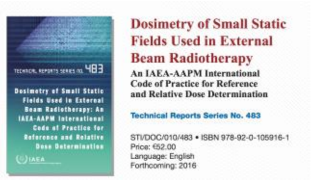
- Section 1: Introduction
  - History
  - Definitions
  - Similarities and Differences Between 3D–CRT, IMRT and SRT
  - *Radiobiological considerations - Issues and Challenges*
  - Clinical experience
- Section 2: Small Field Dosimetry
- Section 3: Definition of Volumes
- Section 4: Treatment Planning Algorithms
- Section 5: Image Guided Beam Delivery
- Section 6: Quality Assurance
- Section 7: Prescribing, Recording and Reporting
- Appendix: Clinical Examples

2009 - 2017
122 pages
excluding references!

Section 2: Small field dosimetry

- Setting up a program for SRT requires dedicated team involving all professions related to the radiation planning & delivery!!
- Small fields - radiation dosimetry is prone to errors – expert knowledge required!!
- ICRU 91 strongly discourages the use of high energies, i.e., for SRT, E ≤ 10 MV!!

Small field dosimetry *à la* ICRU 91 follows verbatim the IAEA-AAPM TRS 483



TECHNICAL REPORTS SERIES NO. 483

Dosimetry of Small Static Fields Used in External Beam Radiotherapy: An IAEA-AAPM International Code of Practice for Reference and Relative Dose Determination

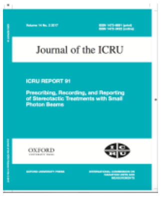
IAEA

Dosimetry of Small Static Fields Used in External Beam Radiotherapy

An IAEA-AAPM International Code of Practice for Reference and Relative Dose Determination

Technical Reports Series No. 483

STI/DOC/010/483 • ISBN 978-92-0-105916-1
Price: €52.00
Language: English
Forthcoming: 2016



Journal of the ICRU

ICRU REPORT 91

Prescribing, Recording, and Reporting of Stereotactic Treatments with Small Photon Beams

OXFORD

Which problems needed to be solved?

- Characteristics that lead to dosimetric issues of two kinds:
  - Reference dose calibration
    - Reference fields are not 10 x 10 cm^2, SSD/SAD is not 100 cm, etc; they are called "machine-specific reference fields" (*msr*)
    - Flattening filter-free beams, beam quality specification
  - Output factors
    - Small fields
    - Detector correction factors
- Problem that was put on the backburner: calibration of composite fields

A new formalism for reference dosimetry of small and nonstandard fields

R. Alfonso

P. Andreo

R. Capote

M. Saiful Huq

W. Kilby

P. Kjäll

T. R. Mackie

H. Palmans

K. Rosser

J. Seuntjens

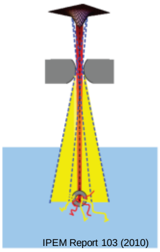
W. Ullrich

S. Vatnitsky

The "Alfonso" paper (2008)

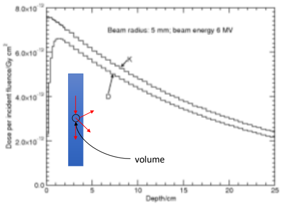
What constitutes small-field conditions?

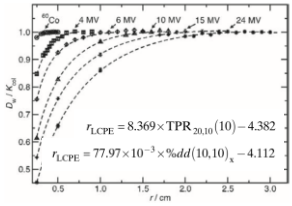
- Beam-related small-field conditions
  - the existence of lateral charged particle disequilibrium
  - change in photon fluence spectrum → beam quality
  - partial geometrical shielding of the primary photon source as seen from the point of measurement
- Detector-related small-field condition
  - detector size compared to field size



IPEM Report 103 (2010)

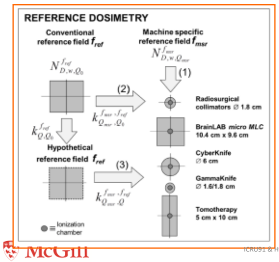
Lateral charged particle loss





In small fields there is **no depth** at which D ≈ K_{col}

Concept of the *msr* field



$$\boxed{D^{f_{msr}}_{w,Q_{msr}} = M^{f_{msr}}_{Q_{msr}} \cdot N^{f_{msr}}_{D,w,Q_{msr}}}$$

Route 1

$$\boxed{D^{f_{msr}}_{w,Q_{msr}} = M^{f_{msr}}_{Q_{msr}} \cdot N^{f_{ref}}_{D,w,Q_0} \cdot k^{f_{msr},f_{ref}}_{Q_{msr},Q_0}}$$

→ $f_{ref=}$=10 x 10 cm^2

→ Q_0= ^{60}Co

Route 2

$$\boxed{D^{f_{msr}}_{w,Q_{msr}} = M^{f_{msr}}_{Q_{msr}} \cdot N^{f_{ref}}_{D,w,Q_0} \cdot k^{f_{ref}}_{Q,Q_0} \cdot k^{f_{msr},f_{ref}}_{Q_{msr},Q}}$$

Route 3

Equivalent square fields *msr*

$$s = \frac{1}{2\pi}\int\int\left(\lambda e^{-\lambda r} - \mu\lambda e^{-\lambda r} + \mu\lambda^2 r e^{-\lambda r}\right)F(r)\,dr\,d\theta$$

Make the scattering component equivalent!

WFF beams:
BJR 25 - equivalent field size is energy independent

FFF beams:
equivalent field size is energy dependent; Tables are provided for 6 MV and 10 MV

WFF

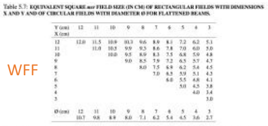


Table 5.7: EQUIVALENT SQUARE *msr* FIELD SIZE (IN CM) OF RECTANGULAR FIELDS WITH DIMENSIONS X AND Y AND OF CIRCULAR FIELDS WITH DIAMETER Ø FOR FLATTENED BEAMS.

Y (cm) X (cm)	12	11	10	9	8	7	6	5	4	3
12	12.0	11.5	10.9	10.3	9.6	8.9	8.1	7.2	6.2	5.1
11		11.0	10.5	9.9	9.3	8.6	7.8	7.0	6.0	5.0
10			10.0	9.5	8.9	8.3	7.5	6.8	5.9	4.8
9				9.0	8.5	7.9	7.2	6.5	5.7	4.7
8					8.0	7.5	6.9	6.2	5.4	4.5
7						7.0	6.5	5.9	5.1	4.3
6							6.0	5.5	4.8	4.1
5								5.0	4.5	3.8
4									4.0	3.4
3										3.0
Ø (cm)	12	11	10	9	8	7	6	5	4	3
	10.7	9.8	8.9	8.0	7.1	6.2	5.4	4.5	3.6	2.7

6 MV FFF

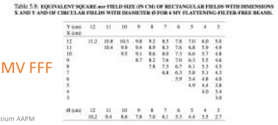


Table 5.8: EQUIVALENT SQUARE *msr* FIELD SIZE (IN CM) OF RECTANGULAR FIELDS WITH DIMENSIONS X AND Y AND OF CIRCULAR FIELDS WITH DIAMETER Ø FOR 6 MV FLATTENING-FILTER-FREE BEAMS.

Y (cm) X (cm)	12	11	10	9	8	7	6	5	4	3
12	11.2	10.8	10.3	9.8	9.2	8.5	7.8	7.0	6.0	5.0
11		10.4	9.9	9.4	8.8	8.3	7.6	6.8	5.9	4.9
10			9.5	9.1	8.6	8.0	7.3	6.6	5.7	4.8
9				8.7	8.2	7.6	7.0	6.3	5.5	4.6
8					7.8	7.3	6.7	6.1	5.3	4.5
7						6.8	6.3	5.8	5.1	4.3
6							5.9	5.4	4.8	4.0
5								4.9	4.4	3.8
4									4.0	3.4
3										3.0
Ø (cm)	12	11	10	9	8	7	6	5	4	3
	10.2	9.4	8.6	7.8	7.0	6.1	5.3	4.4	3.5	2.7

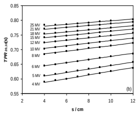
Getting the beam quality in non-standard reference fields

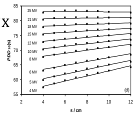
for $\mathrm{TPR}_{20,10}(10) = \mathrm{TPR}_{20,10}$

$$\boxed{\mathrm{TPR}_{20,10}(10) = \frac{\mathrm{TPR}_{20,10}(S) + c(10-S)}{1 + c(10-S)}}$$

for $\%dd(10,10) = \%dd(10,10)_X = \%dd(10)_X$

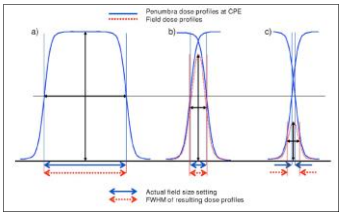
$$\boxed{\%dd(10,10) = \frac{\%dd(10,S) + 80c(10-S)}{1 + c(10-S)}}$$





Note: FFF beams → use the Pb filter and equations in TG-51 to get $\%dd(10,10)_X$

Source occlusion



Das et al. 2008 Med Phys **35**: 206-15

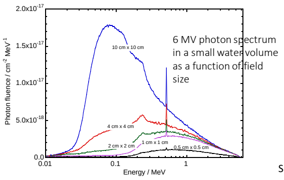
Overlapping of beam penumbras

FWHM > geometric field size

Small field dosimetry-related parameters must be specified as a function of FWHM

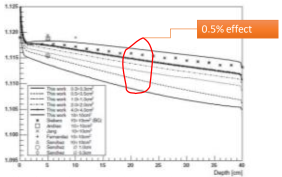
Spectral changes

- The photon fluence spectrum is modified as a function of field size



6 MV photon spectrum in a small water volume as a function of field size

Benmakhlouf Sempau Andreo
Med. Phys. **41** (2014)



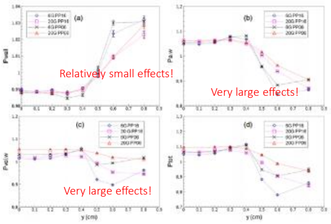
0.5% effect

Spectral hardening does not lead to large changes in stopping power ratio!

Eklund and Ahnesjö, Phys Med Biol 53:4231 (2008)

Magnitude of *p* correction factors on- and off-axis

8 mm x 8 mm field, 10 cm depth (0.6 mm, 2 mm spot sizes)

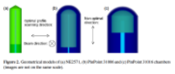


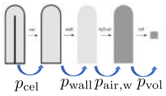
Relatively small effects!

Very large effects!

Very large effects!

PP31006 and PP31016 chambers





Crop et al., Phys Med Biol 54:2951 (2009)

→ Small field output measurements need to be corrected for these effects!

Concept of field output correction factors

- Field output factor relative to reference field (ref stands here for a conventional reference or msr field)

$$\boxed{\Omega^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}} = \frac{M^{f_{clin}}_{Q_{clin}}}{M^{f_{ref}}_{Q_{ref}}} \cdot k^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}}}$$

- Field output factor relative to reference field using intermediate field or 'daisy chaining' method

$$\boxed{\Omega^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}} = \frac{M^{f_{clin}}_{Q_{clin}}(\text{det})}{M^{f_{\text{int}}}_{Q_{\text{int}}}(\text{det})} \cdot \frac{M^{f_{\text{int}}}_{Q_{\text{int}}}(IC)}{M^{f_{ref}}_{Q_{ref}}(IC)} \cdot K^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}}}$$

where $\boxed{K^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}} = k^{f_{clin},f_{\text{int}}}_{Q_{clin},Q_{\text{det}}}(\text{det}) \cdot k^{f_{\text{int}},f_{ref}}_{Q_{\text{int}},Q_{ref}}(IC)}$

Output factors are DOSE RATIOS not reading ratios!!

Small field output correction factors

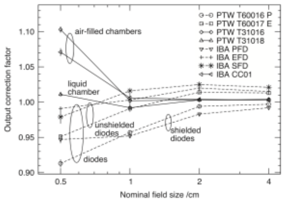


Figure 2.10. Output correction factors, $k^{f_{\text{clin}},f_{\text{msr}}}_{Q_{\text{clin}},Q_{\text{msr}}}$, for eight detector types in small fields from the Varian IX series for 5 mm, 1, 2, and 4 cm field openings normalized to a 10 × 10 cm^2 field

Field size specification

$$S_{\text{clin}} = \sqrt{A \cdot B}$$
$$0.7 < A/B < 1.4$$
$$S_{\text{clin}} = r \cdot \sqrt{\pi}$$

- There are large corrections to reading of virtually any type of detector
- For air-filled chambers: large upwards correction factors in small fields
- For solid state detectors: correction factors depend on the construction, density, Z and size of the sensitive volume

ICRU 91 detector suitability criteria for small fields

- the sensitive region of the detector is close to water equivalent in terms of radiation absorption characteristics;
- the density of the sensitive region is close to the density of water; and
- the size of the sensitive region can be made small compared to the field size while keeping noise levels under control.

ICRU Report 91 - Table of Contents

Section 4: Treatment Planning Algorithms

- Factor based
  - Successfully used in cranial SRS
- Model based
  - Beam model
    - coupled angular - energy distribution of a representative set of particles in the beam (photons and contamination particles)
    - Source parameters - TPS parameterizes the source size – impact on dose calculation accuracy
    - Collimation system - Backup collimation, alignment of different collimation systems
  - Patient model
    - Type a (or category 1)
      - equivalent path-length scaling for inhomogeneity corrections
    - Type b (or category 2)
      - changes in lateral electron transport are considered in some fashion
      - Advanced type-b: MC or deterministic transport algorithms

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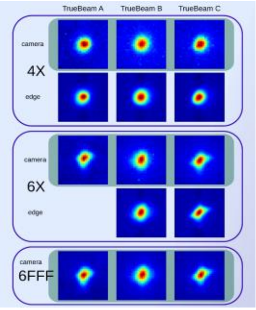
Beam models suitable for SRT planning algorithms are accelerator spot size dependent



Variability in source intensity distribution. Spot sizes range between 2.5 mm and 4.6 mm and the typical spot size is also not perfectly circular

Special care must be taken to commission and validate the beam models in the TPS for use with SRT!

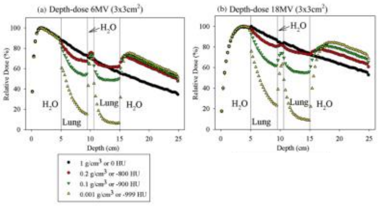


Figure 4.5 Monte Carlo-calculated central-axis depth-dose profiles for a lung slab phantom geometry irradiated by a 6 MV and a 18 MV beam (3 x 3 cm^2 field size) with a 1 × 1 × 1 cm^3 tumour embedded in the lung, with decreasing lung slab density. From Disher et al (Disher, *et al.*, 2012) with permission

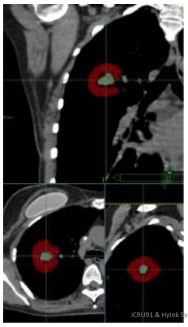


Figure 4.6 Region of dose difference exceeding 15 Gy outside the GTV, between equivalent path length correction (EPL) and Monte Carlo for CyberKnife (6 MV) treatments of a tumor with size 3.6 cm^3. Dose prescribed 60 Gy. From Lacornerie et al (Lacornerie, *et al.*, 2014) with permission.

→ **ICRU Report 91 mandates** the use of advanced type b model-based dose calculation algorithms (Monte Carlo, etc)

Considerations for Clinical Prescription Using Category 2 Dose Calculation Algorithms in Small Fields

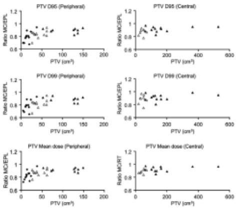


Figure 4.7 Ratio of MC and EPL calculated PTV $D_{95\,\%}$, $D_{99\,\%}$ and mean dose for peripheral and central pulmonary tumors. Bold diamonds represent tumors <3 cm, open triangles represent tumors of 3–5 cm and bold triangles represent tumors >5 cm. Data is for the CyberKnife 6 MV beam. With permission from van der Voort van Zyp et al (van der Voort van Zyp, *et al.*, 2010).

Take home

- ICRU 91 covers
  - the clinical context of SRT
  - small field physics → IAEA-AAPM recommendations
  - TPS dose calculation algorithms
  - IGRT and QA
  - volumes and prescription, recording and reporting
- Does not dive into radiobiology of high dose per fraction nor normal tissue response models
- Tries to systematize and document how SRT is performed clinically

ICRU 91 Reporting

~~Level 1:~~
~~Basic Techniques~~

~~Dose at ICRU reference point~~

Level 2:
Advanced Techniques

DVHs calculated
PTV: $D_{50\%}$, $D_{near\text{-}min}$, $D_{near\text{-}max}$
GTV/CTV/ITV: D50% must for Lung
OAR/PRV: Vol, D_{mean}, V_D, $D_{2\%}$
Dose Homogeneity and Conformity and Gradient Index

Level 3:
Developmental Techniques

In addition: Integral Dose
Biology based evaluation metrics