Radiation protection of specific patient categories (such as children, pregnant women) & associated uncertainties

Liliana Stolarczyk on behalf of EURADOS WG9
Danish Centre for Particle Therapy, Aarhus, Denmark

EURADOS European Radiation Dosimetry Group

Eurados - European Radiation Dosimetry Group

- The association (established in 1982) serves the promotion of R&D and European cooperation in the field of the dosimetry of ionizing radiation
- The scope of EURADOS: **radiation protection, retrospective dosimetry, individual and environmental radiation monitoring, radiobiology, and diagnostic and therapeutic applications of radiation in medicine**
- More than 80 members (institutions) and 600 associate members (scientists), 8 working groups
- https://eurados.sckcen.be/

Members of EURADOS

EURADOS Working Groups

WG2 Harmonization of Individual Monitoring (M.A Chevallier, France)

WG3 Environmental Dosimetry (A. Vargas, Spain)

WG6 Computational Dosimetry (H. Rabus, Germany)

WG7 Internal Dosimetry (D. Broggio, France)

WG9 Dosimetry in Radiotherapy (L. Stolarczyk, Denmark)

WG10 Retrospective Dosimetry (L. Ainsburry, UK)

WG11 High-Energy Radiation Fields (M. Caresana, Italy)

WG12 Dosimetry in Medical Imaging (P. Ferrari, Italy)

Pilot group: Dosimetry in Nuclear Medicine (Weibo Li, Germany)

https://eurados.sckcen.be/working-groups/wg9-radiation-dosimetry-radiotherapy

WG9 experiment in ATreP, Trento, 2013

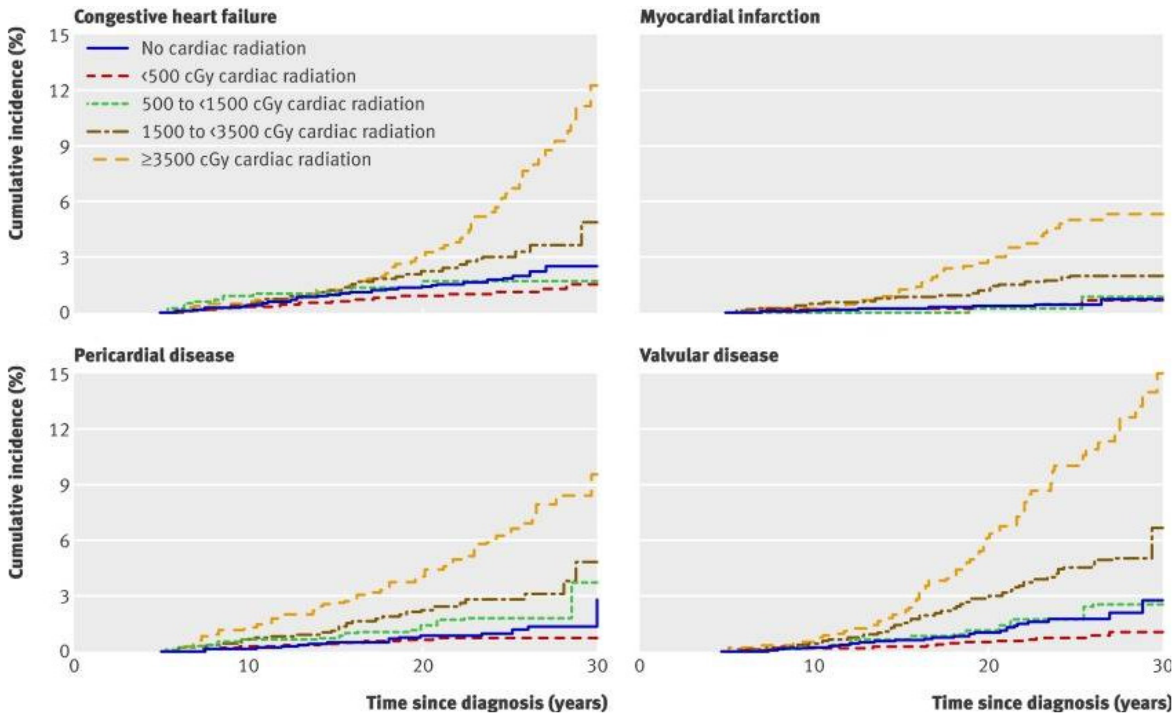
WG9 experiment in CCB IFJ PAN, Krakow, 2017

EURADOS Working Group 9
Radiation Dosimetry in Radiotherapy

- Task Groups
  - Small field photon beam dosimetry (Hrvoje Hršak)
  - Out-of-field doses in brachytherapy (Joao Santos, Saveta Miljanic)
  - Computational methods in medical physics (Hrvoje Brkić)
  - Hadron radiotherapy programme (Pawel Olko)
- Scientific programme
  - **Dosimetry of out-of-field patient dose**
  - Total dose to the patient from therapy and imaging
  - Small field dosimetry
  - Specific developments in proton and neutron dosimetry
  - Monte Carlo simulation studies
  - New and emerging dosimetric techniques and materials

Concerns with respect to nontarget radiation

- Cardiac toxicity
- Implantable pacemakers and other electronic devices
- Cataracts
- Skin dose
- Secondary cancers (paediatric patients)
- Foetal doses



Mulrooney, Daniel A et al. "Cardiac outcomes in a cohort of adult survivors of childhood and adolescent cancer: retrospective analysis of the Childhood Cancer Survivor Study cohort." *BMJ (Clinical research ed.)* vol. 339 b4606. 8 Dec. 2009, doi:10.1136/bmj.b4606

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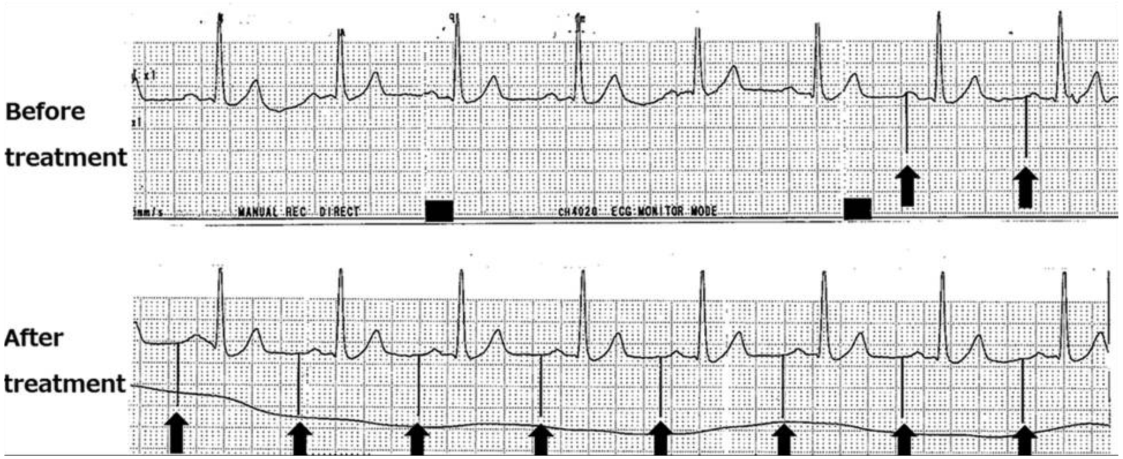

Ueyama T, Arimura T, Ogino T, et al. Pacemaker malfunction associated with proton beam therapy: a report of two cases and review of literature-does field-to-generator distance matter?. Oxf Med Case Reports. 2016;2016(8):omw049. Published 2016 Aug 29. doi:10.1093/omcr/omw049.

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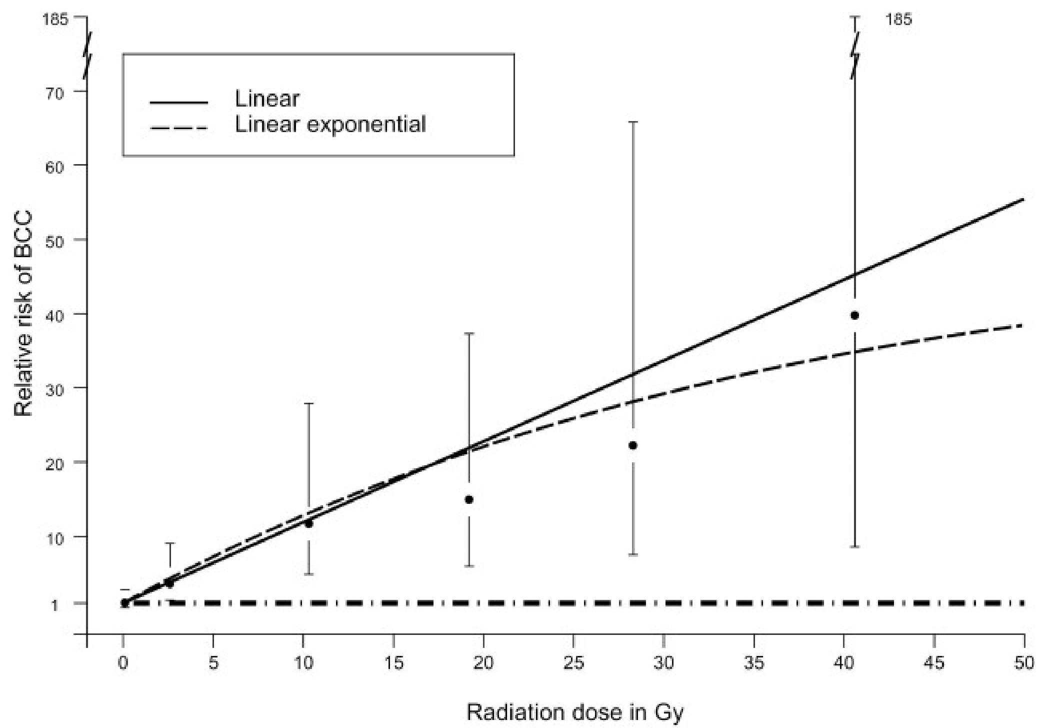

Watt TC, Inskip PD, Stratton K, et al. Radiation-related risk of basal cell carcinoma: a report from the Childhood Cancer Survivor Study. J Natl Cancer Inst. 2012;104(16):1240–1250. doi:10.1093/jnci/djs298.

Concerns with respect to nontarget radiation

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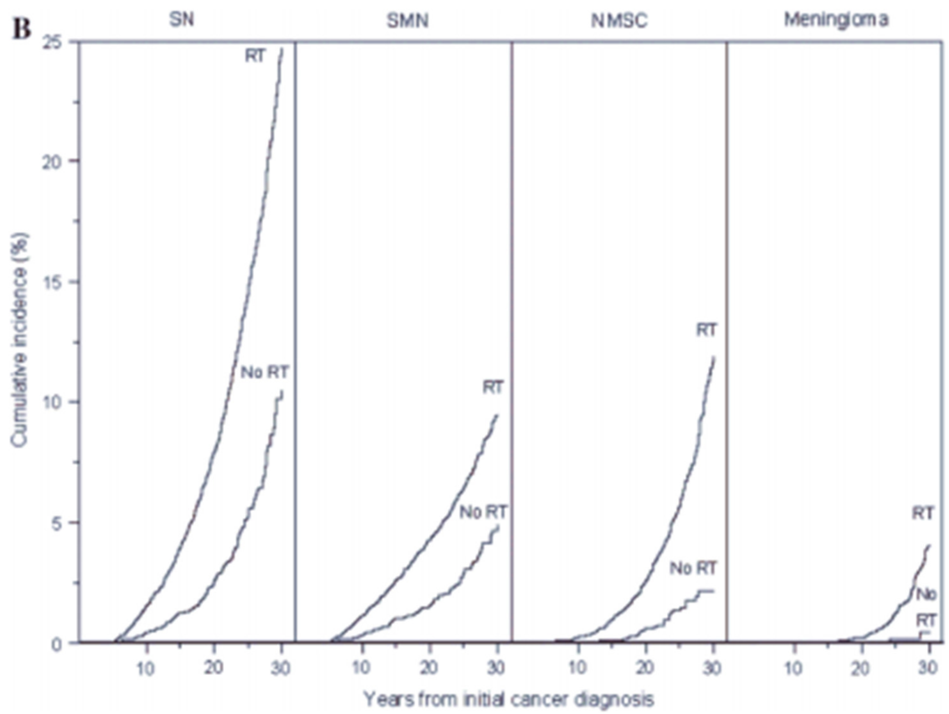

Friedman et al., Subsequent Neoplasms in 5-Year Survivors of childhood cancer: the childhood cancer Survivor Study JNCI J Natl Cancer Inst (2010) 102(14): 1083-1095.

Concerns with respect to nontarget radiation

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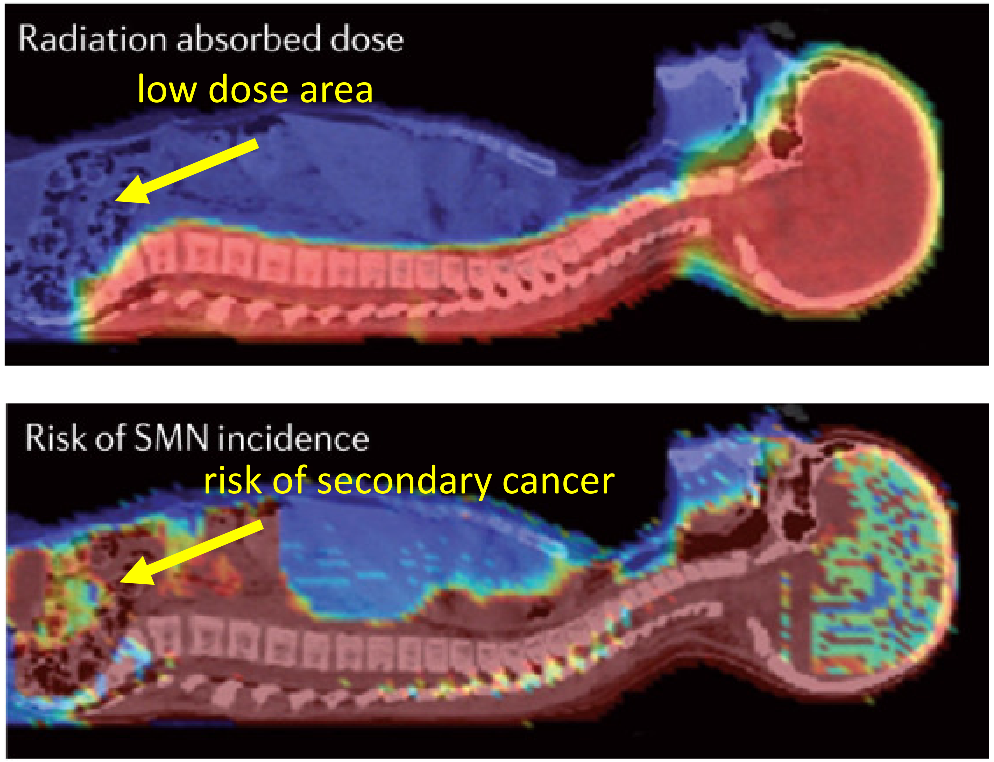

Newhauser W., Durante, M., Assessing the risk of second malignancies after modern Radiotherapy. Nat Rev Cancer. 2011 June ; 11(6): 438–448.

Concerns with respect to nontarget radiation

- Secondary cancers (paediatric patients)
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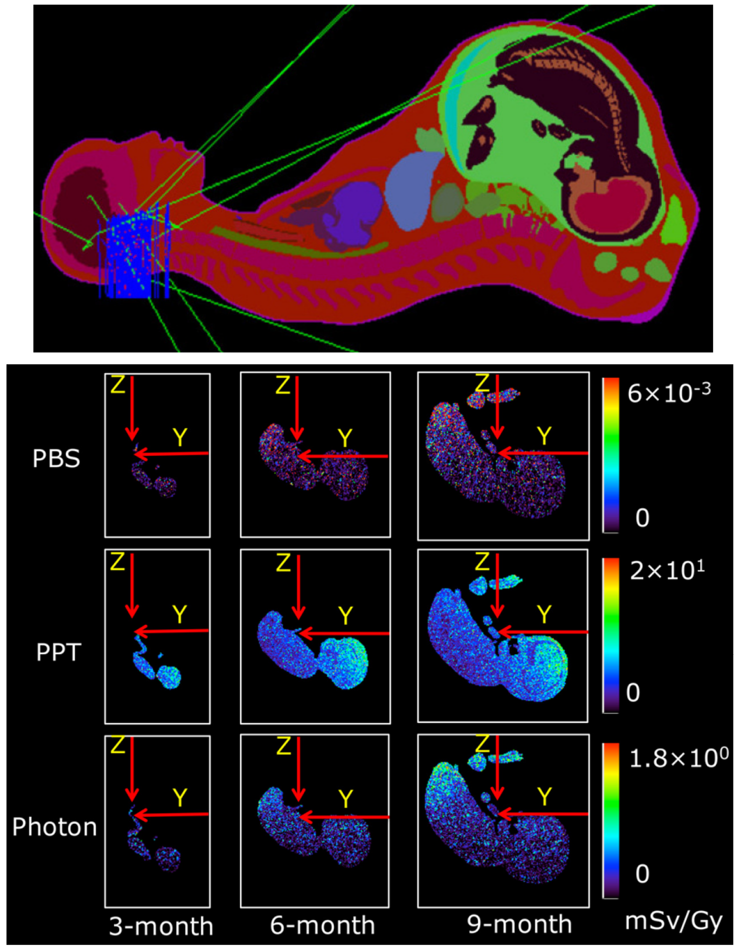


Geng C, Moteabbed M, Seco J, Gao Y, Xu XG, Ramos-Méndez J, Faddegon B, Paganetti H., Dose assessment for the fetus considering scattered and secondary radiation from photon and proton therapy when treating a brain tumor of the mother. Phys Med Biol. 2016 Jan 21;61(2):683-95. doi: 10.1088/0031-9155/61/2/683. Epub 2015 Dec 30.

Sensitive patients groups

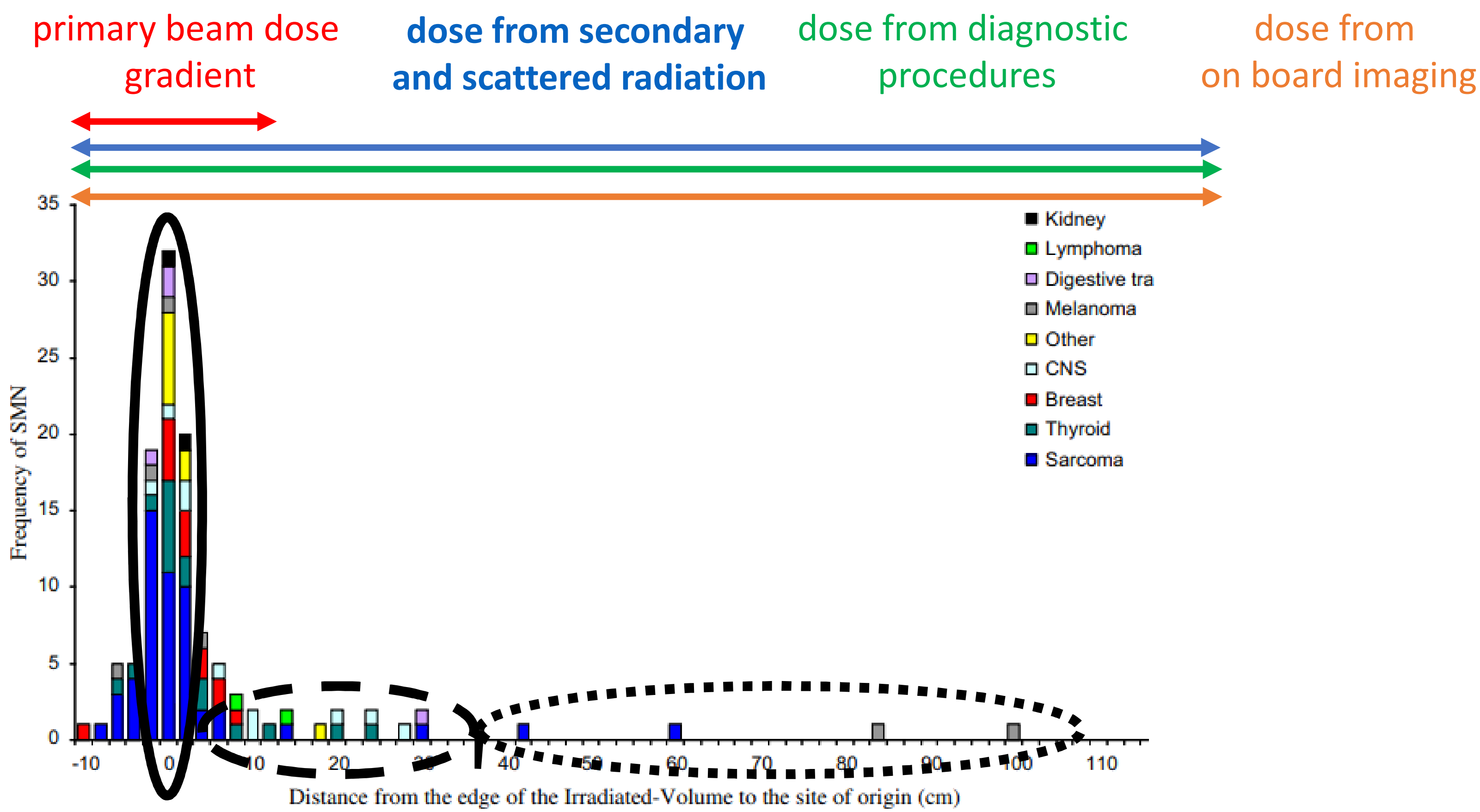
- 5% of cancers occur in children, with approximately **300000 new cases annually** (aged 0-19 years).
- **70% of children with cancer are successfully treated**, with radiation therapy being the primary method.
- Secondary cancer risk post-radiation therapy is up to **10 times higher in children** compared to adults
- **1 in 1000 pregnancies involves cancer** (mainly breast and brain cancers).
- Despite 70% of pregnant patients receiving cancer treatment, **radiotherapy is only applied in 3%,** primarily due to limited data on fetal risk

https://www.bbc.com/news/av/uk-england-leeds-54455060

From radiotherapy mask to brave superhero

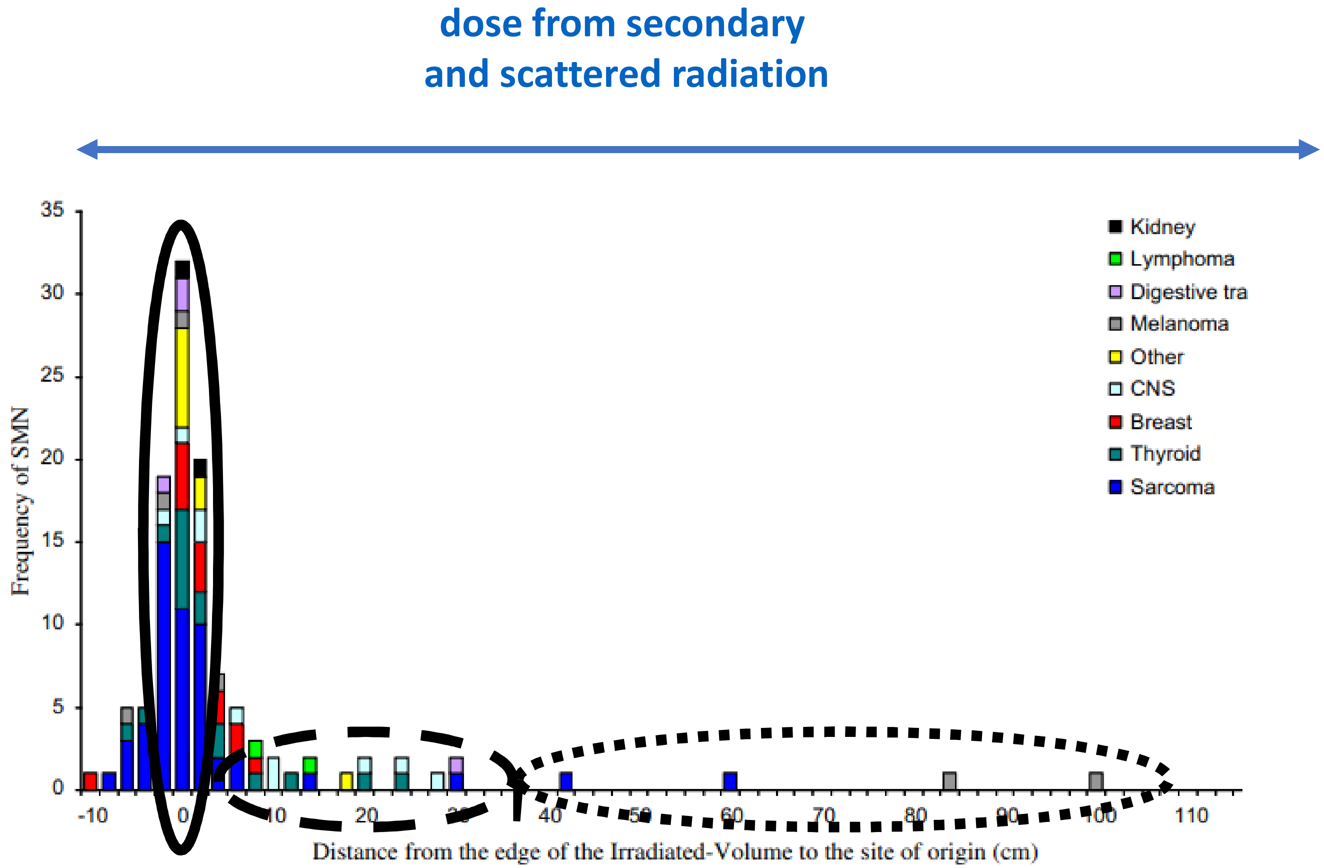
www.iarc.fr/
Cancer Research UK, http://www.cancerresearchuk.orgNovember,2021.
Amercian cancer society, http://www.cancer.org/, November, 2021

Out-of-field doses in radiotherapy



Diallo et al., Int. J. Radiation Oncology Biol. Phys., Vol. 74, No. 3, pp. 876–883, 2009

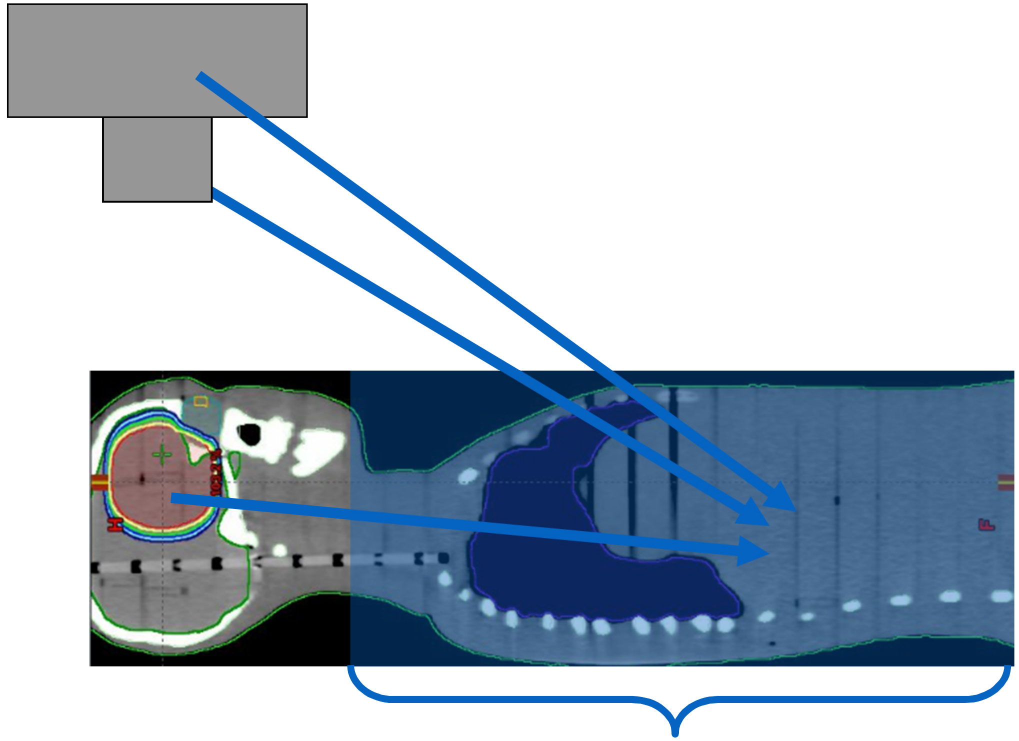
Out-of-field doses in radiotherapy



Diallo et al., Int. J. Radiation Oncology Biol. Phys., Vol. 74, No. 3, pp. 876–883, 2009

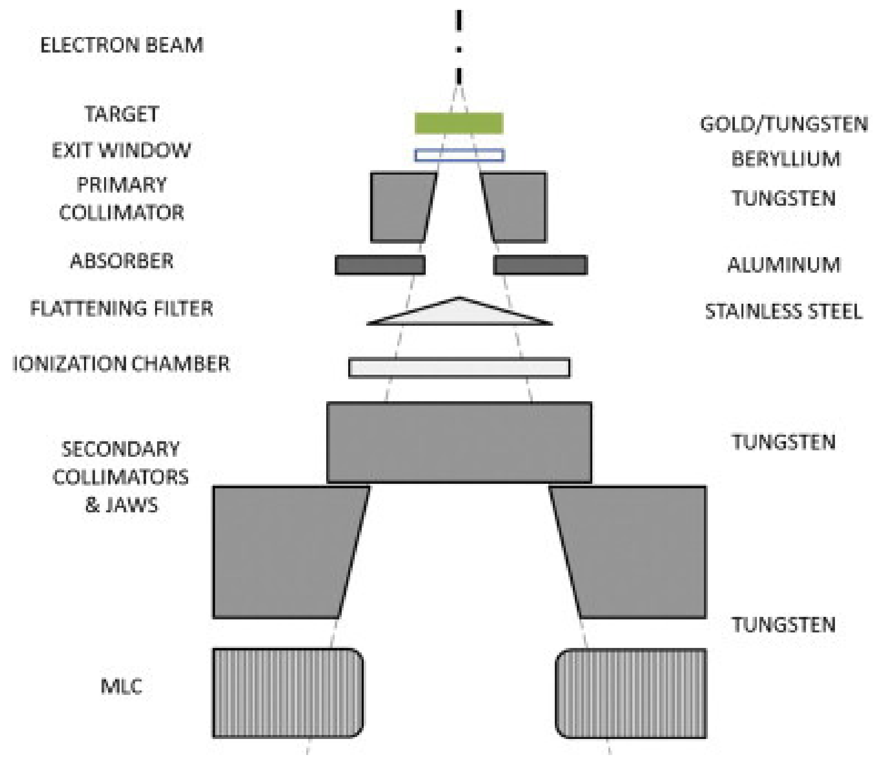
Secondary and scattered radiation in radiotherapy

- Sources of secondary and scattered radiation: **treatment nozzle, patient body**
- **X-rays radiotherapy: scattered X-rays**, secondary γ radiation, **photoneutrons**
- **Proton radiotherapy: neutrons**, charged particles, **secondary γ radiation**, characteristic X-rays, bremsstrahlung radiation, residual radiation from radioactivation



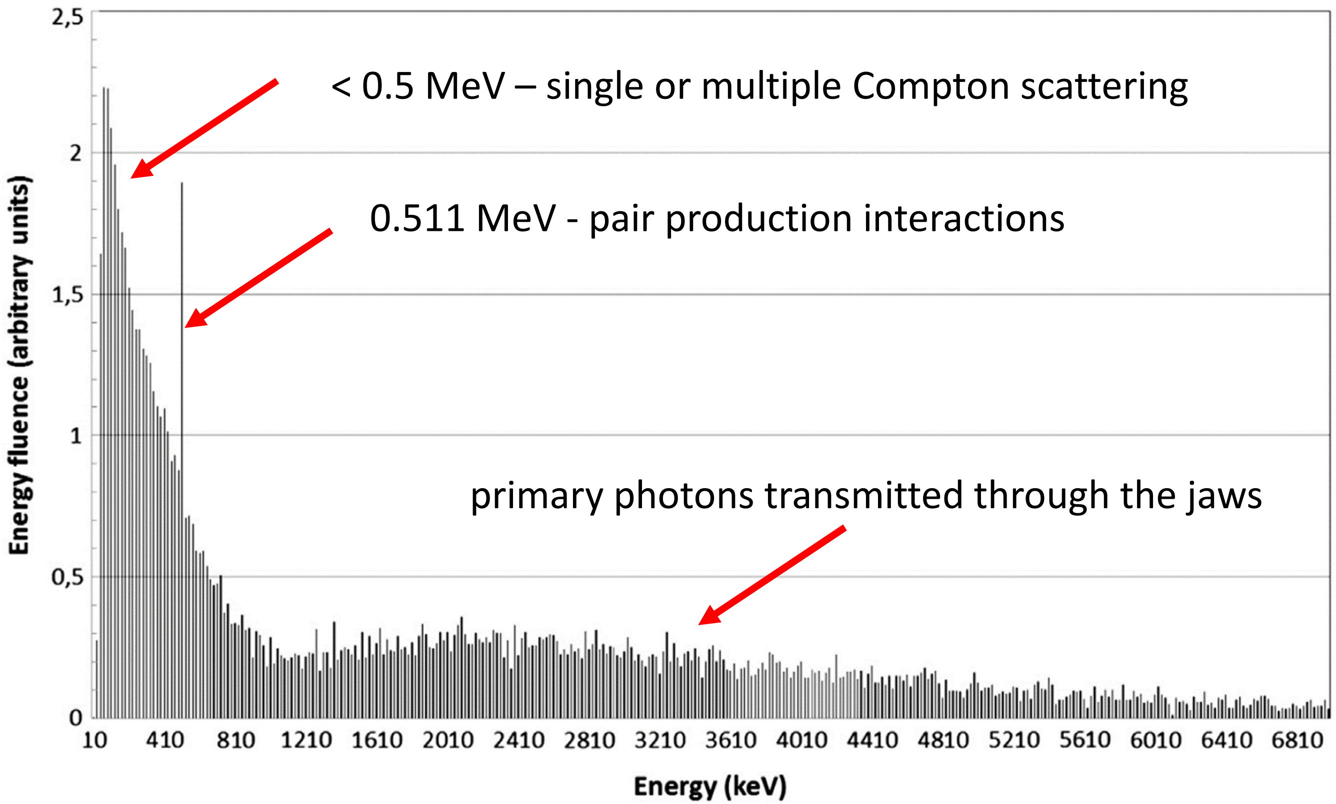
Sources of scattered and secondary radiation for photon beams

- **Collimator scatter**: radiation scattered in the head of the accelerator exits the accelerator through the treatment field
- **Head leakage**: radiation penetrates through the accelerator head shielding
- **Photoneutrons** produced by interaction of photon beam with accelerator components (target, primary collimator, flattener and jaws/collimators)
- Dependence on: field size, MU number, materials, accelerator type, beam energy, treatment technique



Di Fulvio, A., Tana, L., Caresana, M., D'Agostino, E., de San Pedro, M., Domingo, C. and d'Errico, F., 2013. Clinical simulations of prostate radiotherapy using BOMAB-like phantoms: results for neutrons. Radiation measurements, 57, pp.48-61.

Scattered photon fluence spectrum in photon radiotherapy



12 MV X-ray, 10x10cm^2 field,

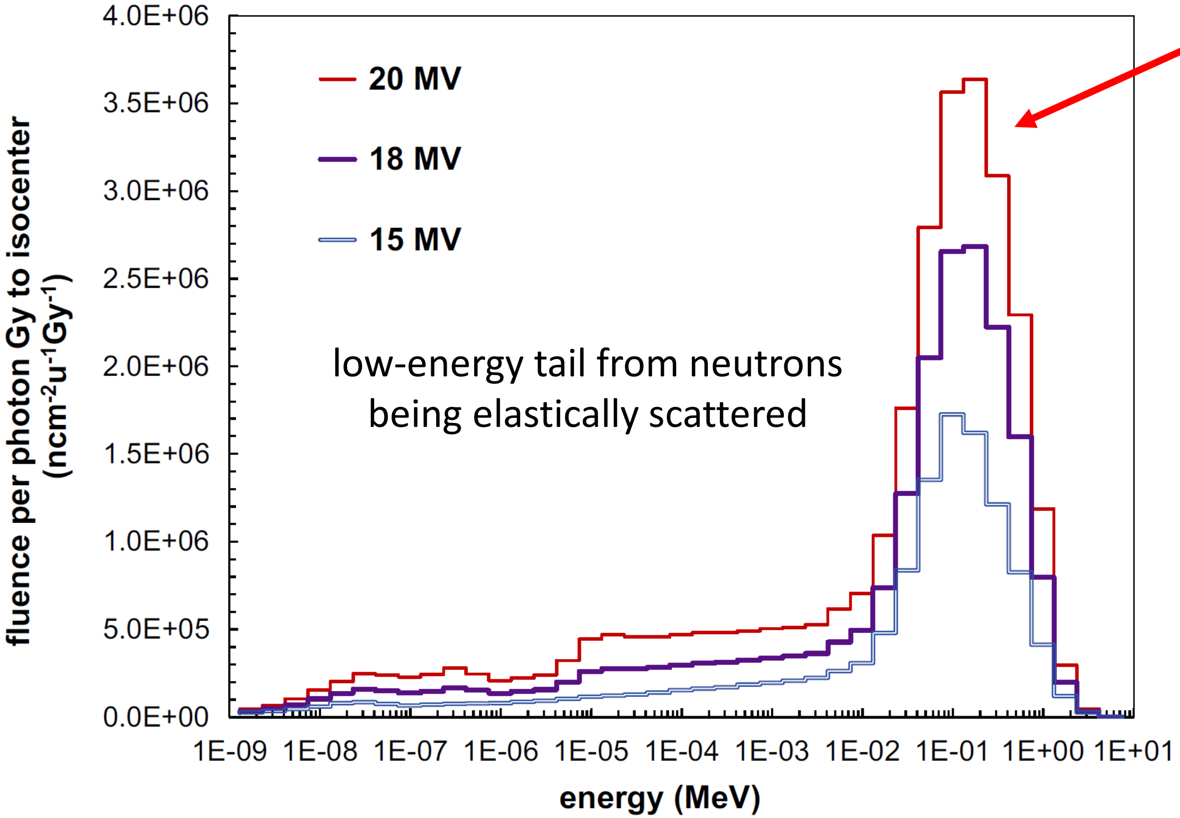
18cm from the beam axis

water tank – MC simulation

Knežević, Ž., Stolarczyk, L., Bessieres, I., Bordy, J.M., Miljanić, S., Olko, P., Photon dosimetry methods outside the target volume in radiation therapy: Optically stimulated luminescence (OSL), thermoluminescence (TL) and radiophotoluminescence (RPL) dosimetry. Radiation Measurements, vol. 57, pp. 9-18

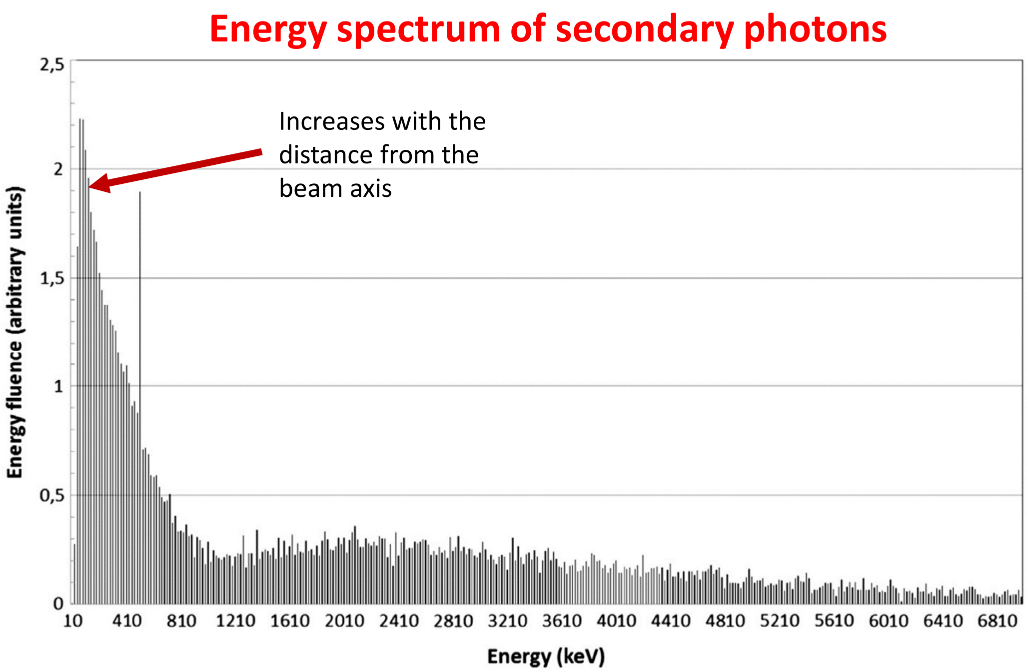
Secondary neutron fluence spectrum in photon radiotherapy

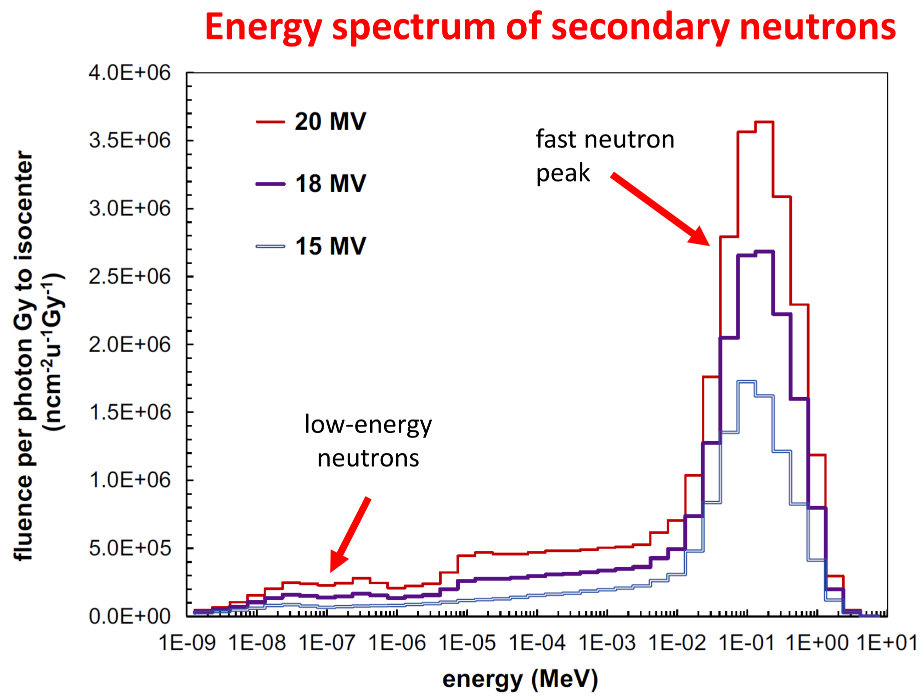
fast neutron peak between 0.1 and 1 MeV



Kry SF, Bednarz B, Howell RM, Dauer L, Followill D, Klein E, Paganetti H, Wang B, Wuu CS, George Xu X, AAPM TG 158: Measurement and calculation of doses outside the treated volume from external-beam radiation therapy. Med Phys. 2017 Oct;44(10):e391-e429. doi: 10.1002/mp.12462. Epub 2017 Aug 20.

Secondary and scattered radiation in photon radiotherapy





Dosimeters with low energy dependence are recommended

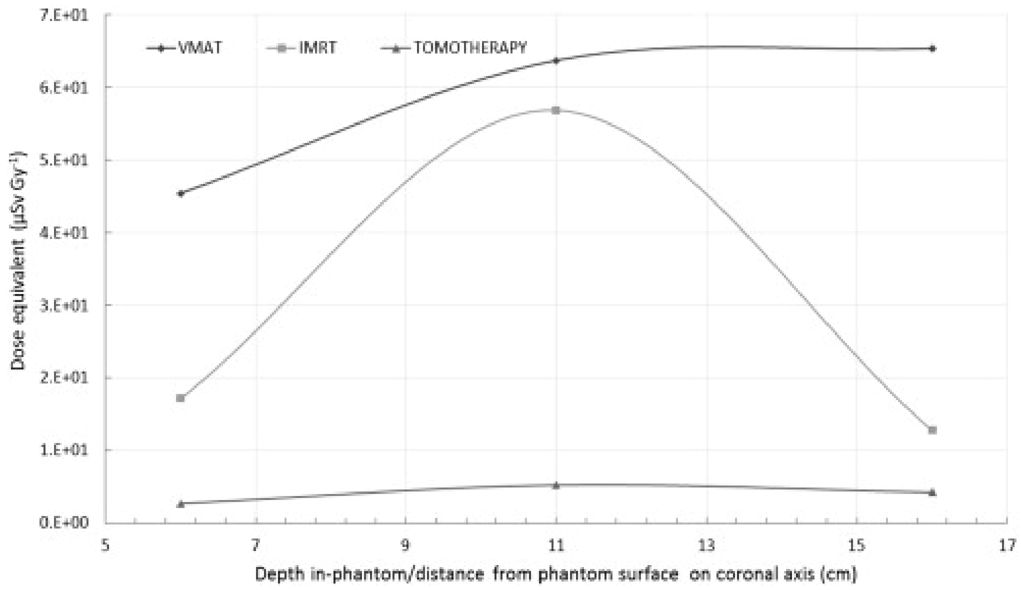
Dosimeters for neutrons 0.1 – 1 MeV are needed

Knežević, Stolarczyk et al, Photon dosimetry methods outside the target volume in radiation therapy: OSL, TL and RPL dosimetry. Radiat Meas 57 (2013) 9-18

Kry et al. AAPM TG 158: Measurement and calculation of doses outside the treated volume from external-beam radiation therapy. Med Phys 44 (2017) e391-e429

Secondary neutrons in photon radiotherapy

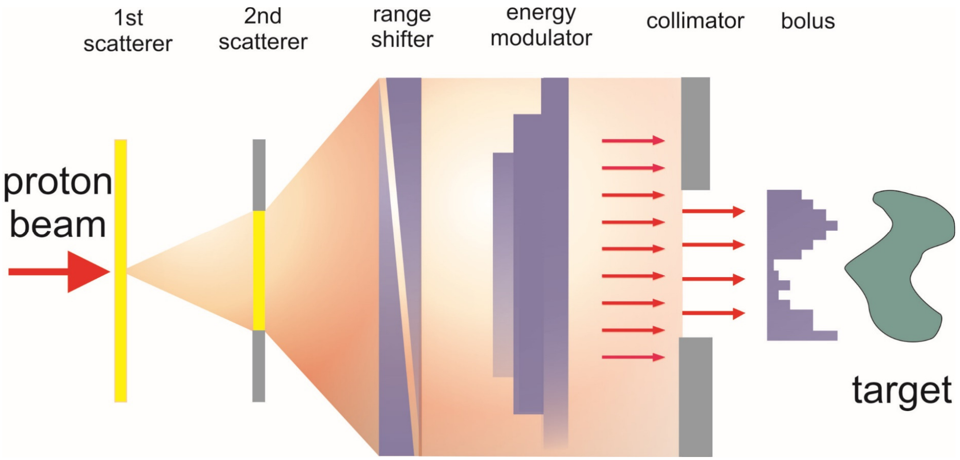
- The probability of photonuclear reactions **increases with photon energy**, however it is not null as long as it is higher than nuclei of interacting materials separation energy (1.66 MeV for beryllium in an accelerator exit window)
- **A non-negligible photoneutron contribution to the total dose has been measured for photon energy qualities as low as 6 MV**



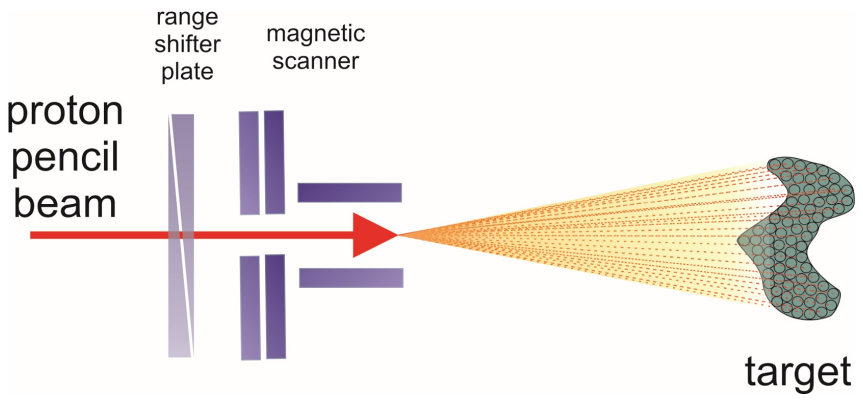
Di Fulvio, A., Tana, L., Caresana, M., D'Agostino, E., de San Pedro, M., Domingo, C. and d'Errico, F., 2013. Clinical simulations of prostate radiotherapy using BOMAB-like phantoms: results for neutrons. Radiation measurements, 57, pp.48-61.

Sources of secondary radiation for proton beams

Passive scattering

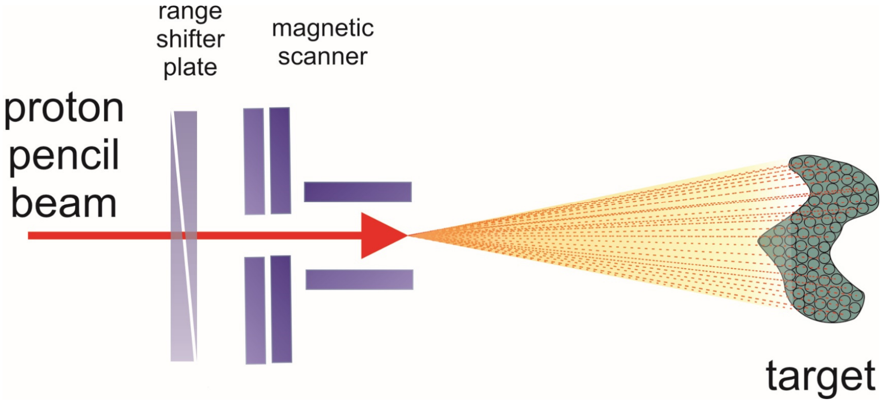


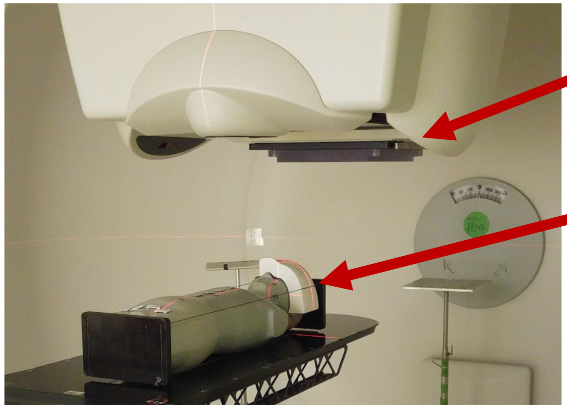
Active Scanning



Sources of secondary radiation for proton beams

- **Beam forming elements** inside the nozzle and close to a patient (collimator, range shifter, compensator)
- **Patient body**
- **Secondary radiation: neutrons and secondary γ radiation**, charged particles, characteristic X-rays, bremsstrahlung radiation, residual radiation from radioactivation



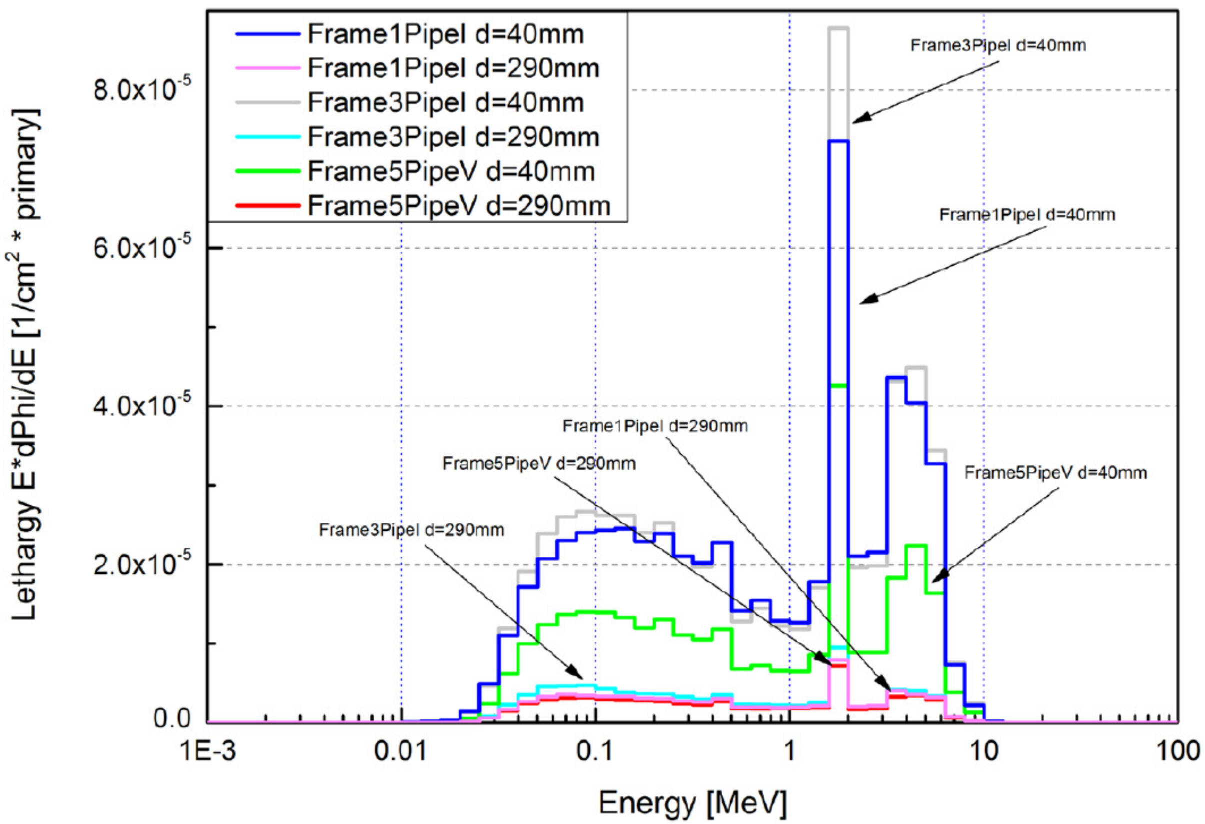


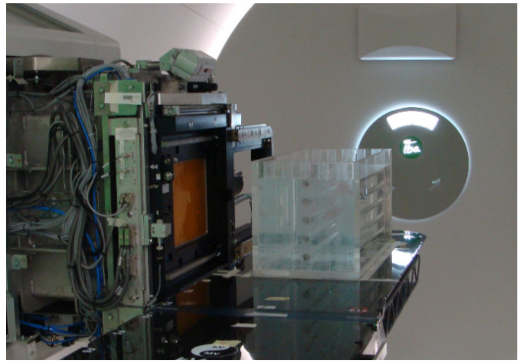
Range shifter

3D printed compensator

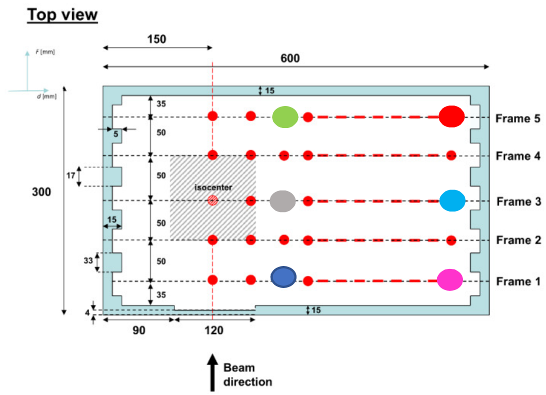
courtesy of A. Wochnik (IFJ PAN)

Secondary photon fluence spectrum in spot scanning proton radiotherapy



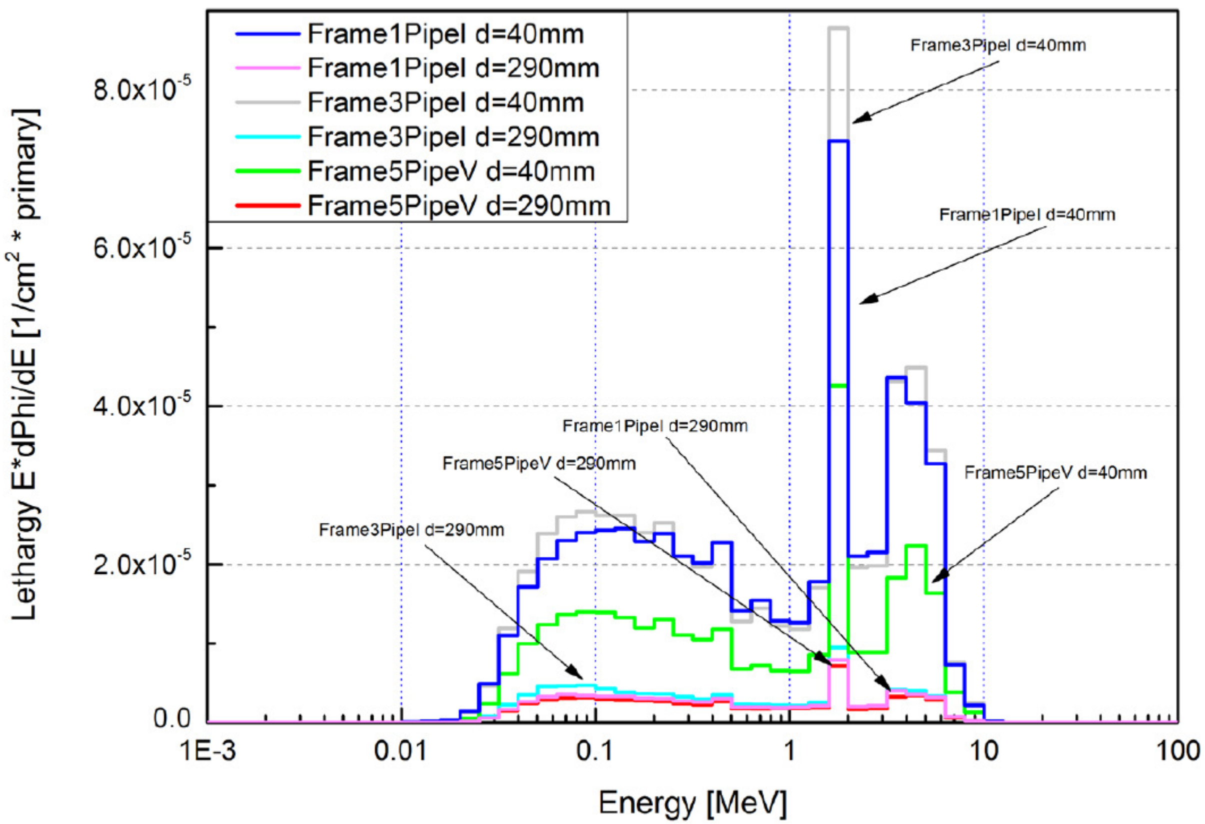


ATreP, Trento



Stolarczyk L, Trinkl S, Romero-Expósito M, Mojżeszek N, Ambrozova I, Domingo C, Davídková M, Farah J, Kłodowska M, Knežević Ž, Liszka M, Majer M, Miljanić S, Ploc O, Schwarz M, Harrison RM, Olko P., Dose distribution of secondary radiation in a water phantom for a proton pencil beam-EURADOS WG9 intercomparison exercise. Phys Med Biol. 2018 Apr 19;63(8):085017. doi: 10.1088/1361-6560/aab469.

Secondary photon fluence spectrum in spot scanning proton radiotherapy



- Total photon fluency decreases with distance from the radiation field
- Dosimeters with flat energy response for (0.01 – 10) MeV are recommended

Stolarczyk L, Trinkl S, Romero-Expósito M, Mojżeszek N, Ambrozova I, Domingo C, Davídková M, Farah J, Kłodowska M, Knežević Ž, Liszka M, Majer M, Miljanić S, Ploc O, Schwarz M, Harrison RM, Olko P., Dose distribution of secondary radiation in a water phantom for a proton pencil beam-EURADOS WG9 intercomparison exercise. Phys Med Biol. 2018 Apr 19;63(8):085017. doi: 10.1088/1361-6560/aab469.

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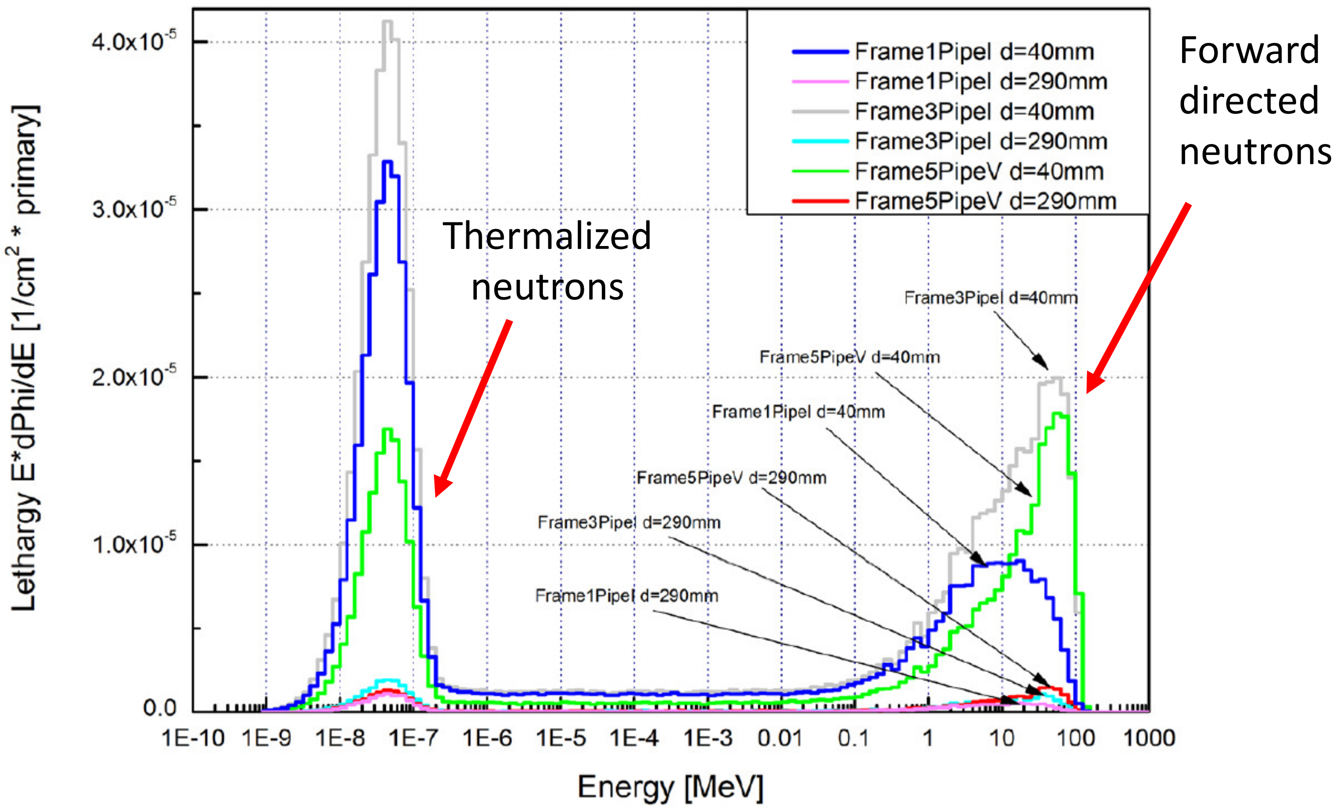
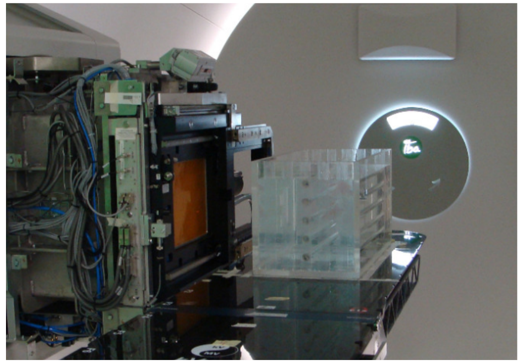
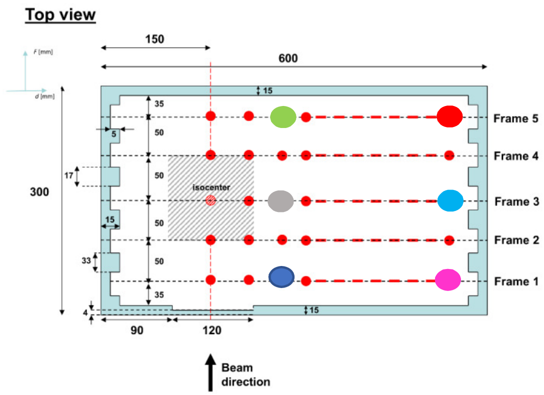




ATreP, Trento



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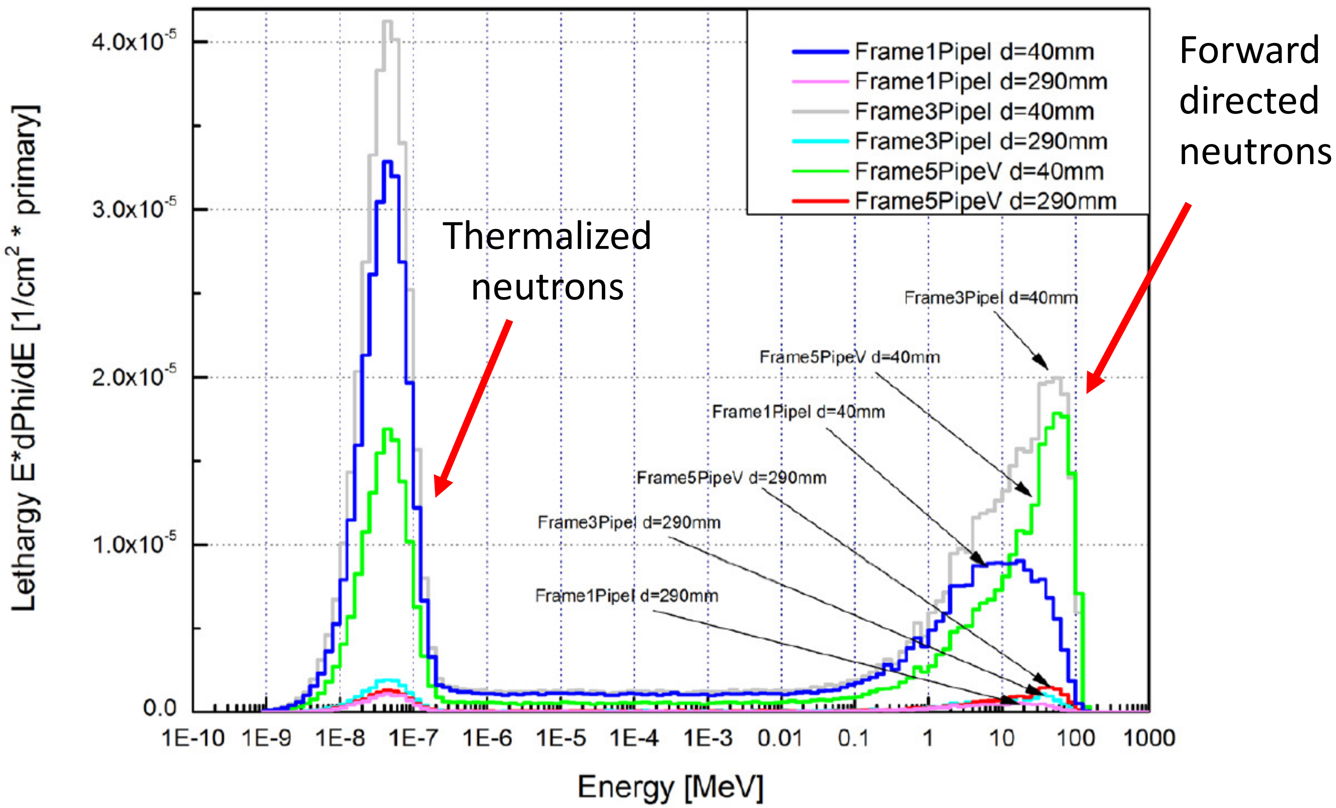
Secondary photon fluence spectrum in spot scanning proton radiotherapy

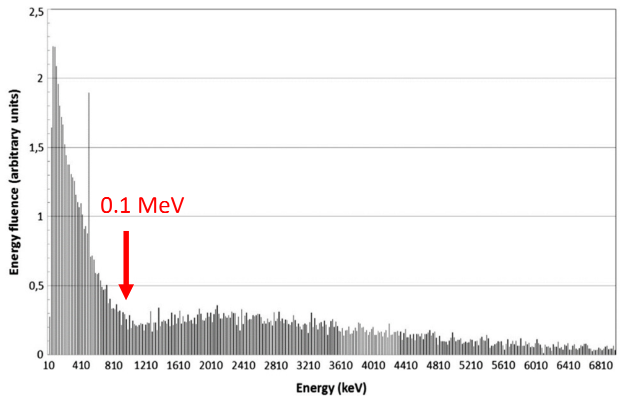


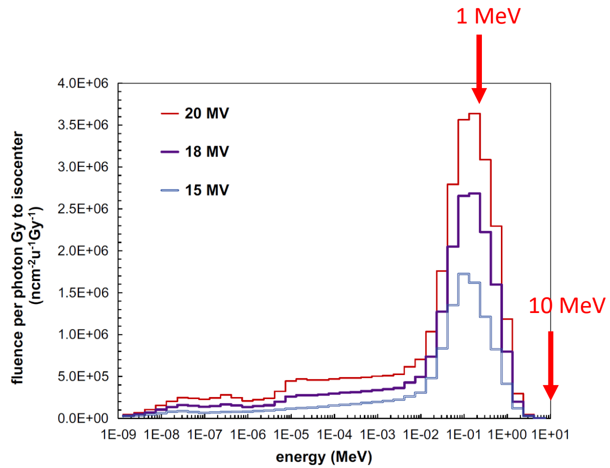
- Total neutron fluence is the highest in the proximity of the proton irradiation
- The ratio between low and high energy neutron fluence changes with position

Stolarczyk L, Trinkl S, Romero-Expósito M, Mojżeszek N, Ambrozova I, Domingo C, Davídková M, Farah J, Kłodowska M, Knežević Ž, Liszka M, Majer M, Miljanić S, Ploc O, Schwarz M, Harrison RM, Olko P., Dose distribution of secondary radiation in a water phantom for a proton pencil beam-EURADOS WG9 intercomparison exercise. Phys Med Biol. 2018 Apr 19;63(8):085017. doi: 10.1088/1361-6560/aab469.

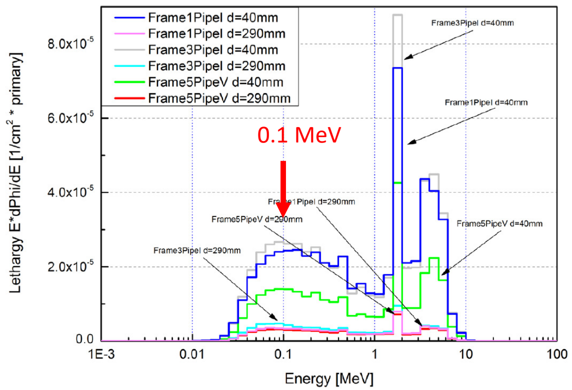
Non-target doses – mixed radiation fields

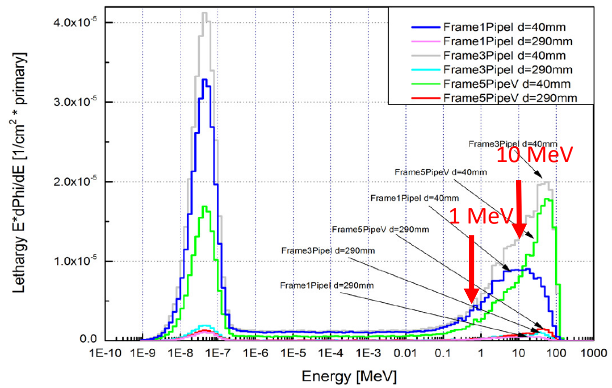
MV X-rays radiotherapy:
scattered X-ray, secondary γ radiation, photoneutrons





Proton PBS radiotherapy:
neutrons, secondary γ radiation, charged particles, bremsstrahlung radiation, characteristic X-rays, residual radiation from radioactivation

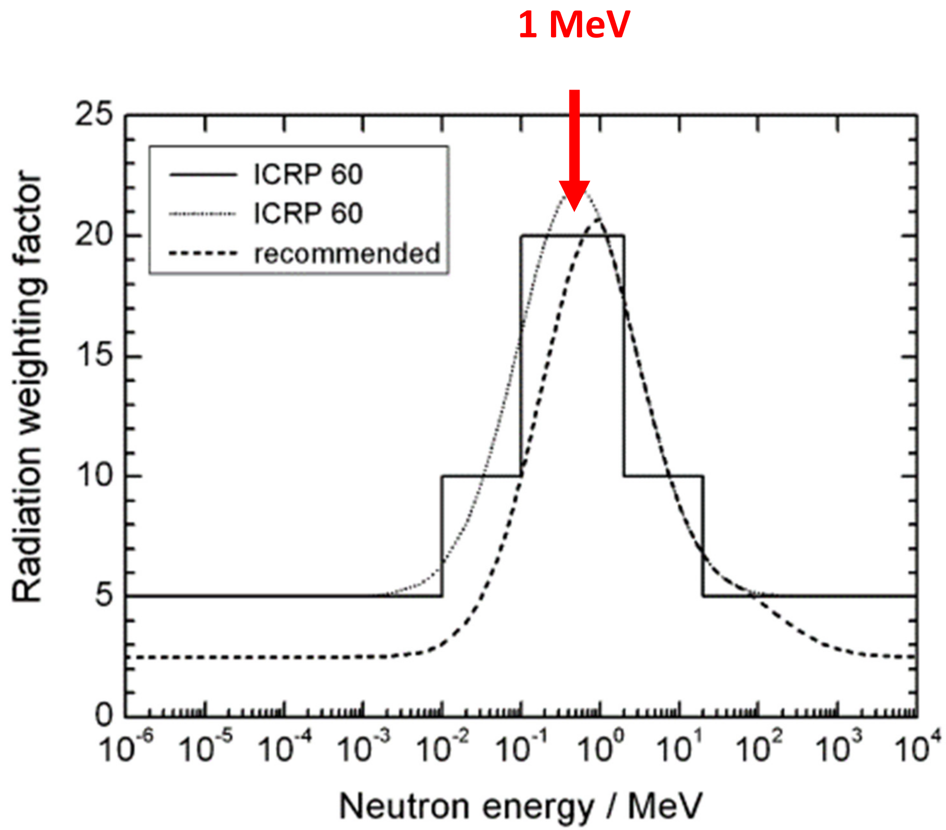




Interactions of neutrons in tissue

- Thermal neutrons
  - Neutron capture by nitrogen
    ^{14}**N(n,p)**^{14}**C**, E_{tr} = 0.62 MeV
  - Neutron capture by hydrogen
    ^{1}**H(n,**γ**)**^{2}**H**, E_{γ}= 2.2 MeV
- Intermediate and fast neutrons
  - Elastic scattering

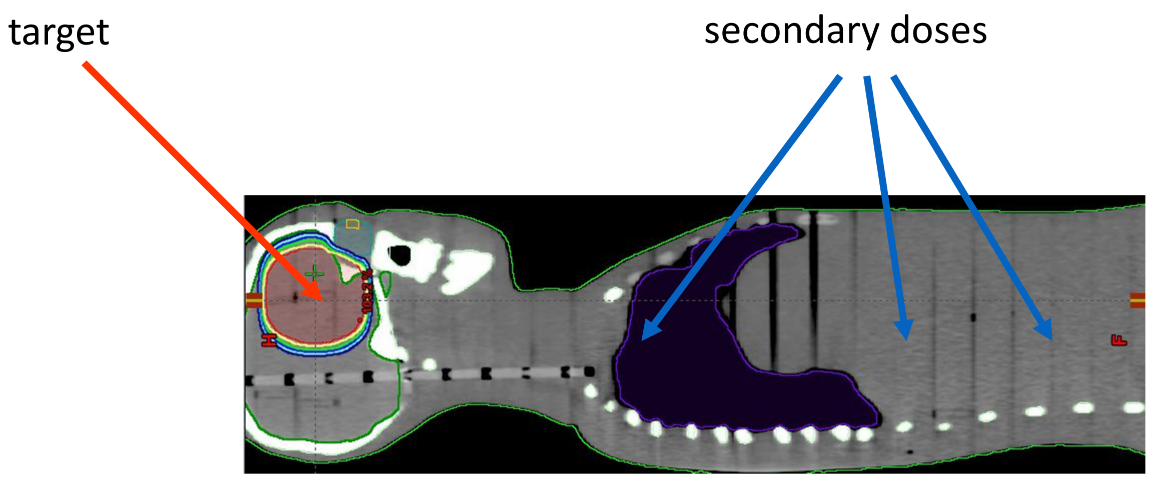
$$\overline{E}_{tr} = E\frac{2M_a M_n}{(M_a + M_n)^2}$$



Secondary doses in radiotherapy

Dose to water
Dose Equivalent
Ambient dose equivalent

$$\frac{\text{Secondary dose}}{\text{Target dose}} \rightarrow \frac{\mu\text{Sv } (\mu\text{Gy})}{\text{Gy}}$$

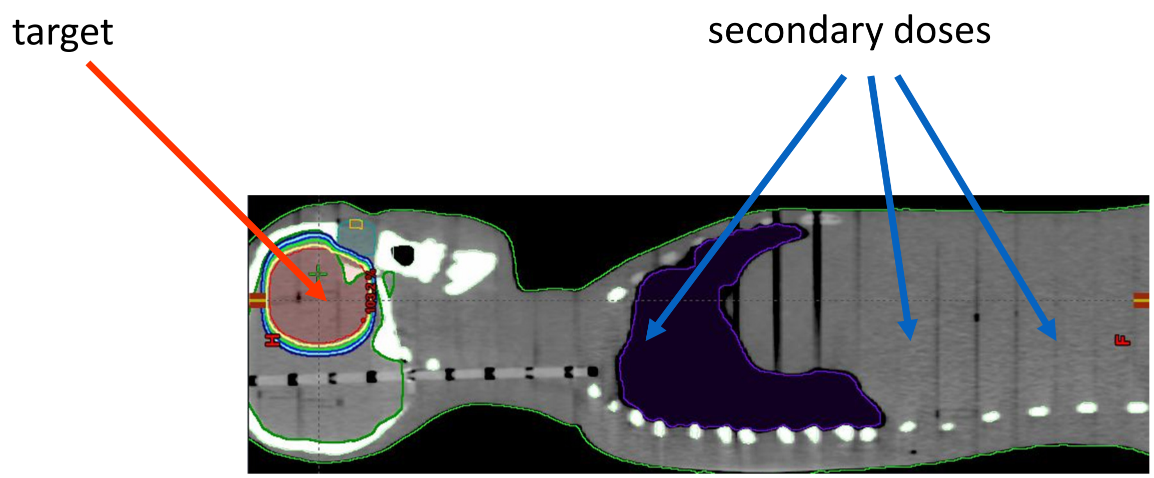


Secondary doses in radiotherapy

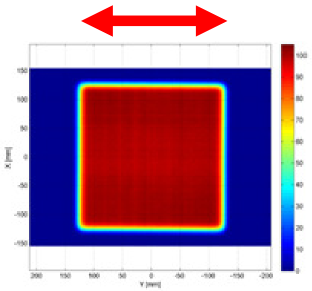
Quantities created for the radioprotection of workers and the general public

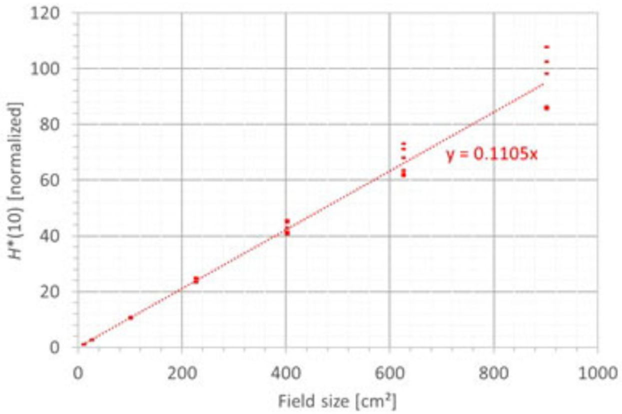
Dose to water
Dose Equivalent
Ambient dose equivalent

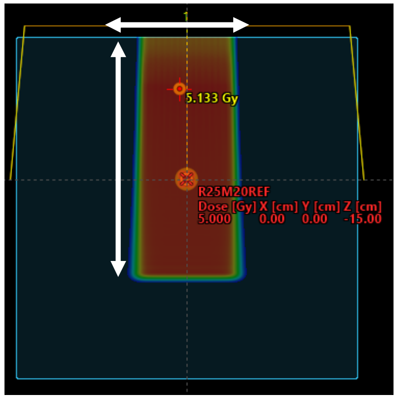
$$\frac{\text{Secondary dose}}{\text{Target dose}} \rightarrow \frac{\mu Sv\ (\mu Gy)}{Gy}$$

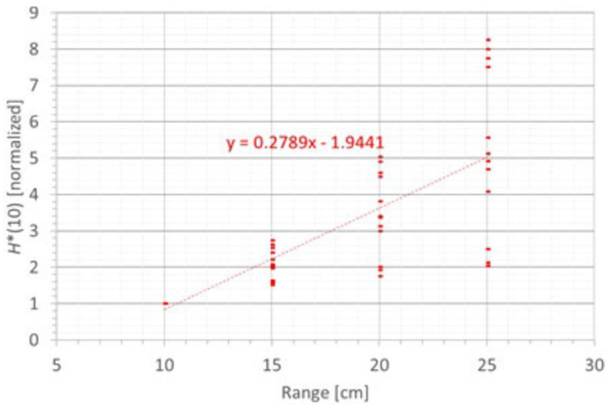


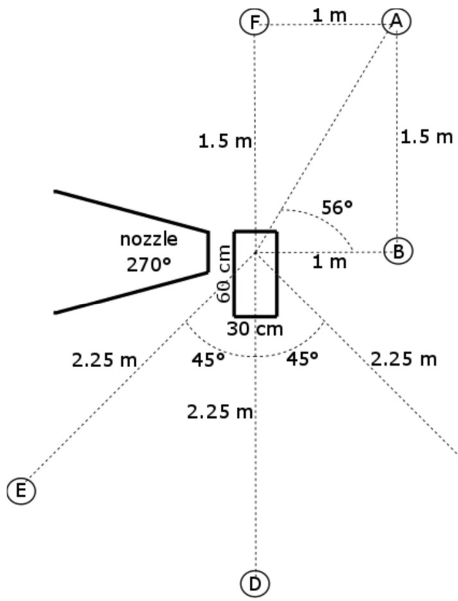
Normalization of out-of-field doses (proton PBS)

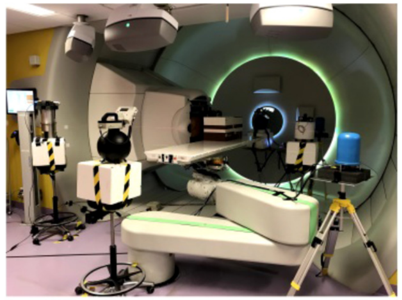












Skandion, Uppsala

CCB, Krakow

Van Hoey, Olivier, Liliana Stolarczyk, Jan Lillhök, Linda Eliasson, Natalia Mojzeszek, Malgorzata Liszka, Ali Alkhiat et al. "Simulation and experimental verification of ambient neutron doses in a pencil beam scanning proton therapy room as a function of treatment plan parameters." Frontiers in Oncology 12 (2022): 903537.

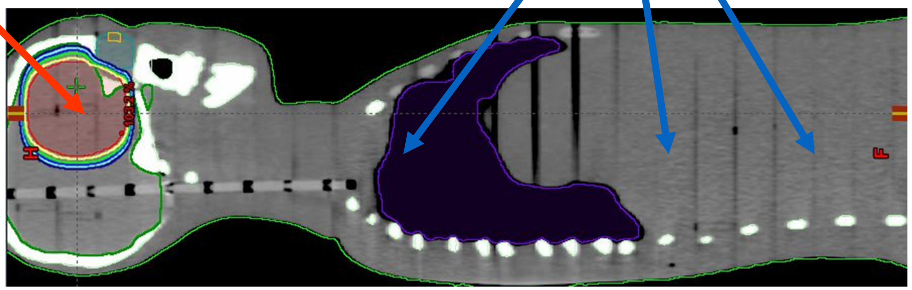
Secondary doses in radiotherapy

Dose to water
Dose Equivalent
Ambient dose equivalent

$$\frac{\text{Secondary dose}}{\text{Target dose}} \rightarrow \frac{\mu\text{Sv} \; (\mu\text{Gy})}{\text{Gy}}$$

target

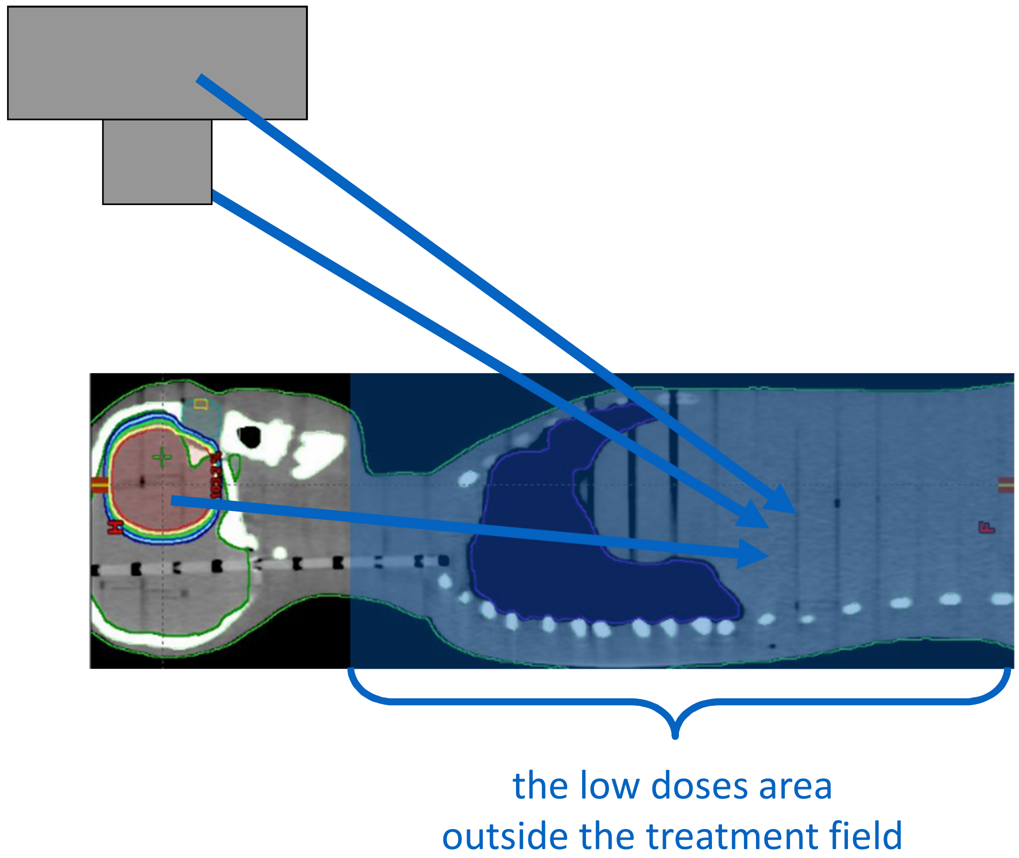
secondary doses



Normalization to dose is meaningful only when the properties of the primary field are known.

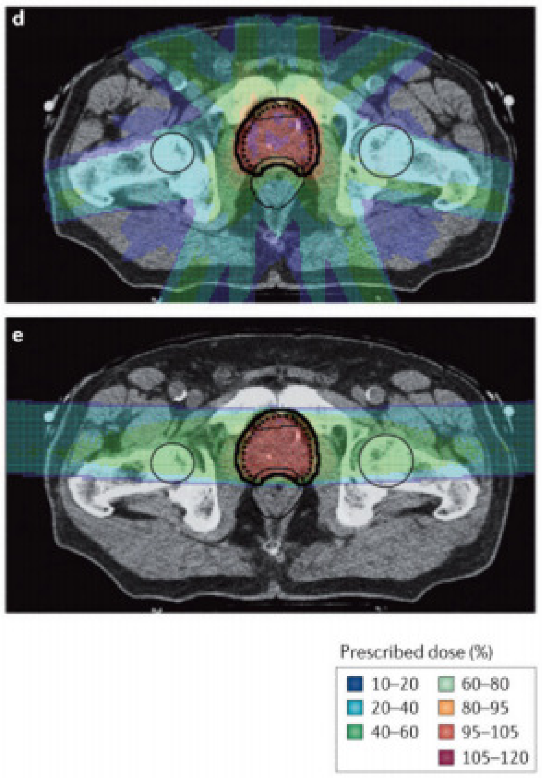
Overview of available dosimetry methods

- Treatment planning systems
- Monte Carlo simulations
- Analytical models of therapeutic and stray absorbed dose
- Literature review
- In-phantom dosimetry



Treatment planning systems

- **Organs in the tumour vicinity** (typically 0.1 Gy to 50 Gy)
- Calculations possible only in the area covered by CT
- No dose from diagnostic and imaging procedures
- Reduced accuracy outside the treatment field
- Scattered and secondary radiation far outside of the target is not taken into account
- Relative biological effectiveness (RBE) of a radiation is not fully considered



Newhauser W., Durante, M., Assessing the risk of second malignancies after modern Radiotherapy. Nat Rev Cancer. 2011 June ; 11(6): 438–448.

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EURADOS OBI Project (WG12 and WG9)

formalism to estimate **absorbed dose at any point in the patient**, including imaging, therapeutic and out-of-field doses

EURADOS European Radiation Dosimetry Group

Treatment planning systems

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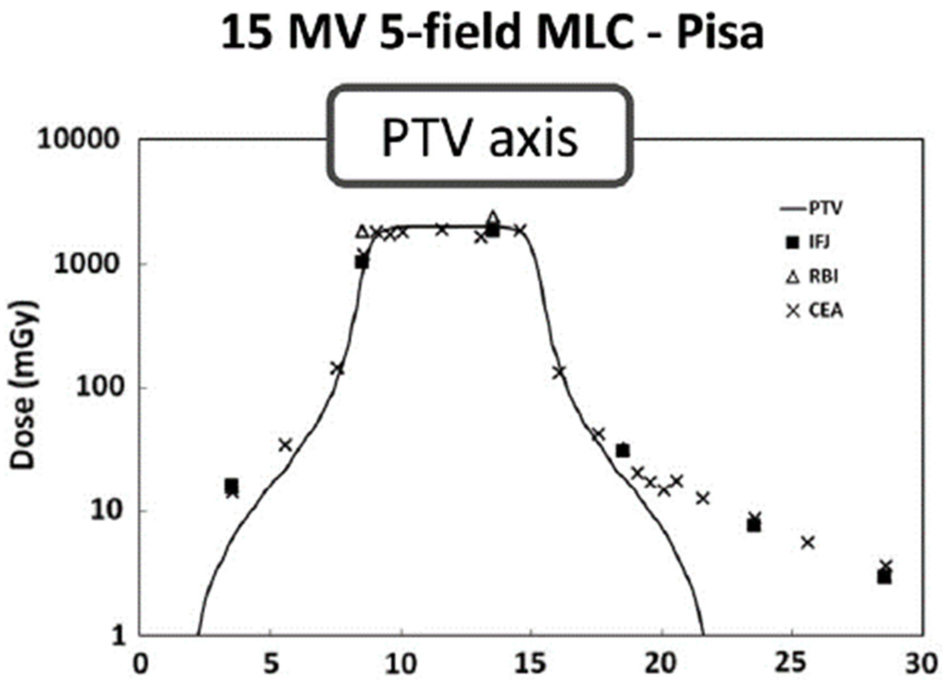
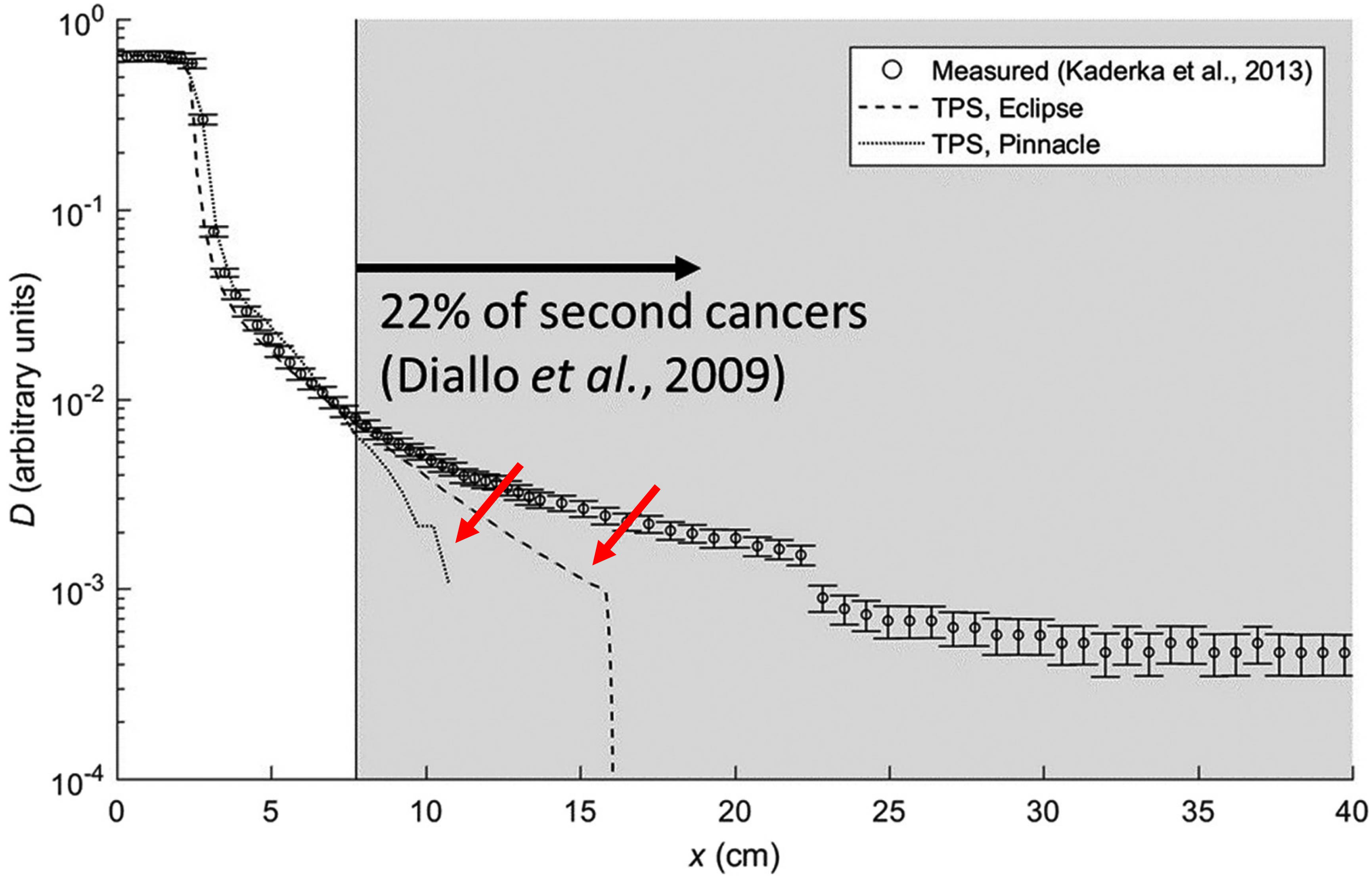


Miljanic S., Bessieres I., Bordy JM., d'Errico F., Di Fulvio A., Kabat D., Knezevic Z., Olko P., Stolarczyk L., Tana L., Harrison R., Clinical simulations of prostate radiotherapy using BOMAB-like phantoms: Results for photons. Radiation Measurements 57 (2013) 35-47



Wilson et al., Method to quickly and accurately calculate absorbed dose from therapeuticand stray photon exposures throughout the entire body in individual patients. Med. Phys. 47 (5), May 2020

Treatment planning systems

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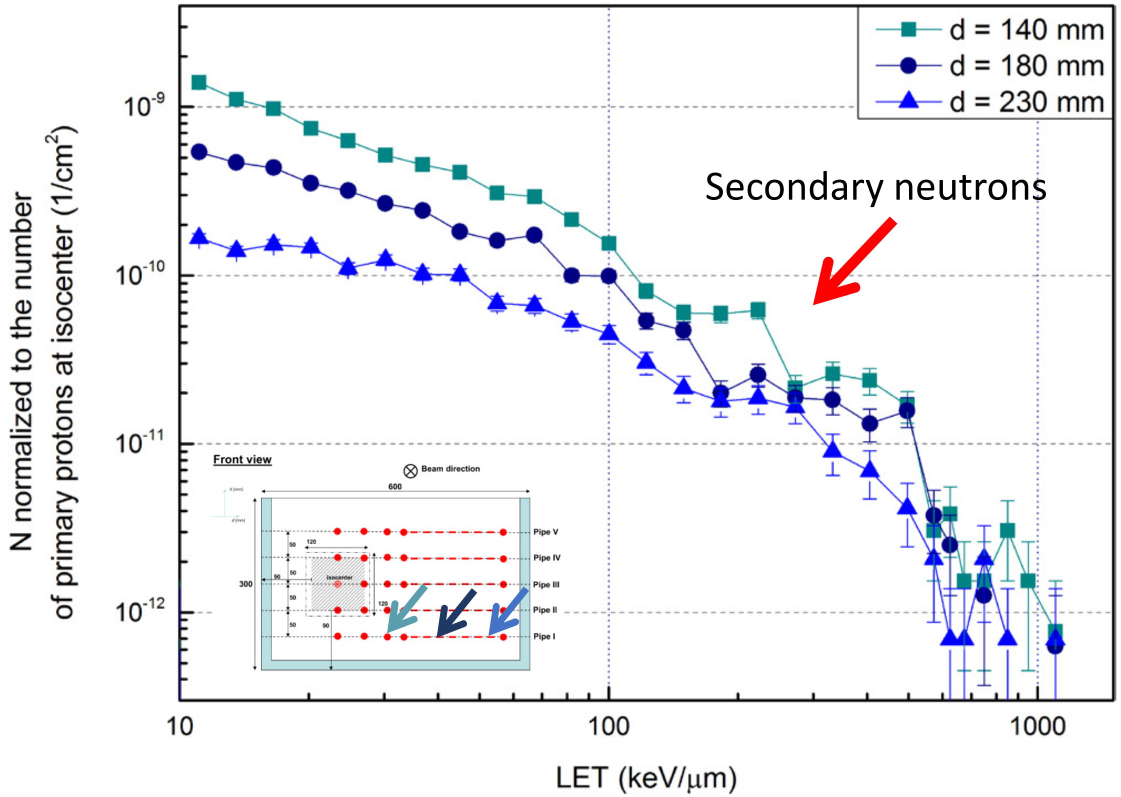
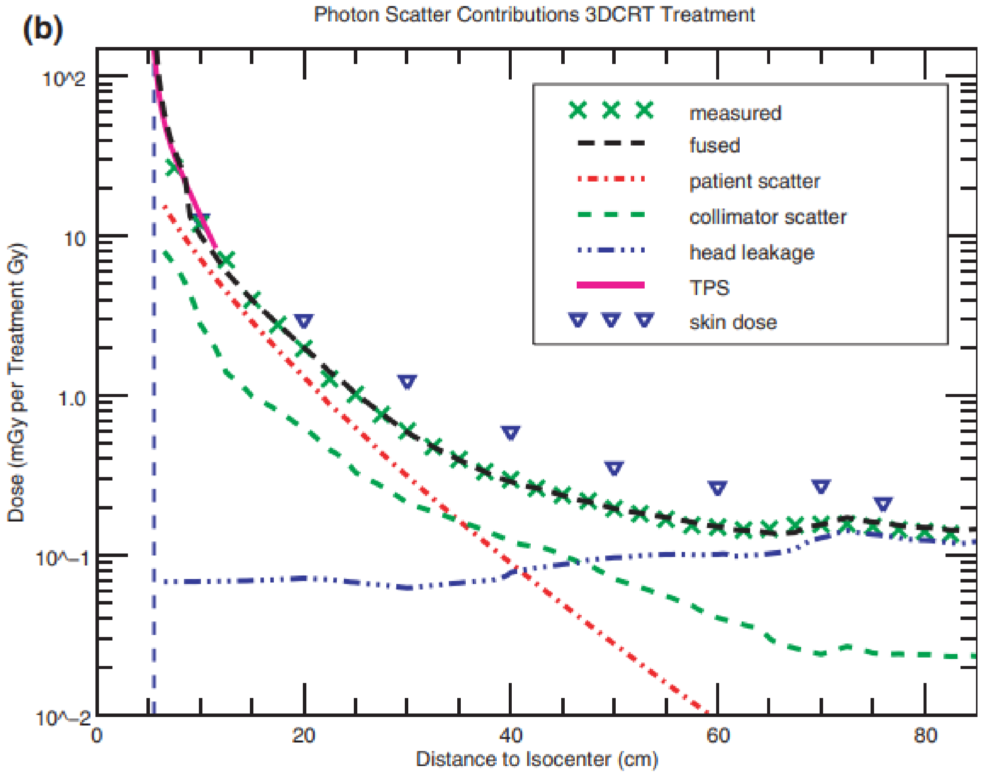


Stolarczyk L, Trinkl S, Romero-Expósito M, Mojżeszek N, Ambrozova I, Domingo C, Davídková M, Farah J, Kłodowska M, Knežević Ž, Liszka M, Majer M, Miljanić S, Ploc O, Schwarz M, Harrison RM, Olko P., Dose distribution of secondary radiation in a water phantom for a proton pencil beam-EURADOS WG9 intercomparison exercise. Phys Med Biol. 2018 Apr 19;63(8):085017. doi: 10.1088/1361-6560/aab469.

Analytical models

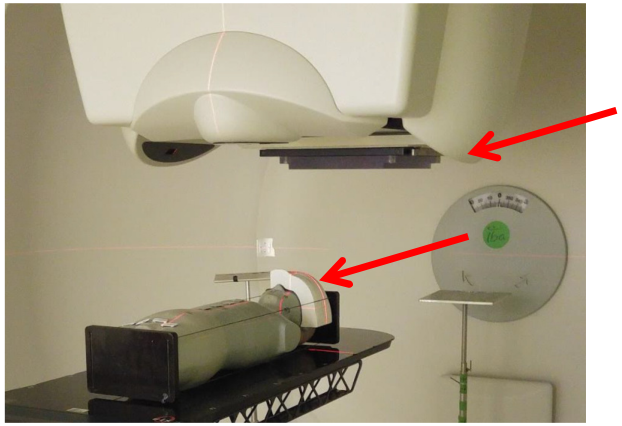
- Accuracy approximately 30%, with potential for larger errors
- Difficult to use in a daily routine (not implemented in TPS)
- Creating detailed models is challenging without accessible manufacturer blueprints
- **Analytical models should be validated against measurements**

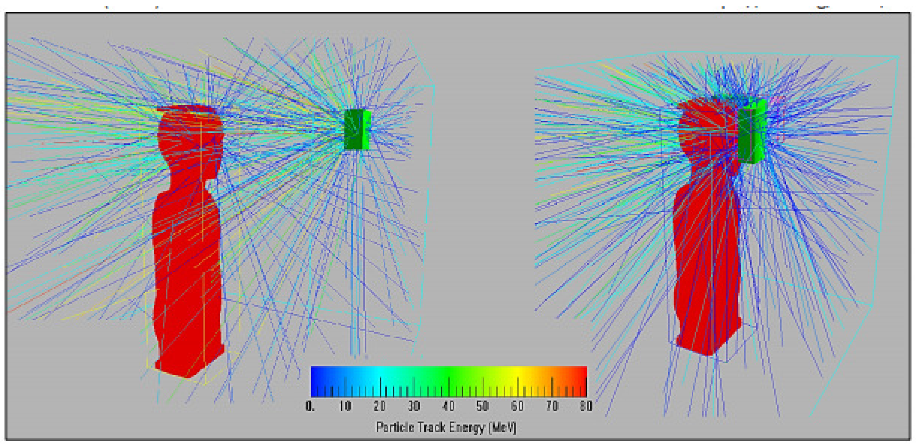


Pascal Hauri, Uwe Schneider, Whole-body dose equivalent including neutrons is similar for 6 MV and 15 MV IMRT, VMAT, and 3D conformal radiotherapy. Journal of Applied Clinical Medical Physics (2019) 20(3) 56-70

Monte Carlo simulations

- **The most accurate method of simulating particle interactions within a medium**
- Huge flexibility (e.g., scoring the dose from different particles or interactions separately)
- Whole-body computational phantoms needed
- Long computation times
- Differences between different MC codes
- **MC simulations should be validated against measurements**

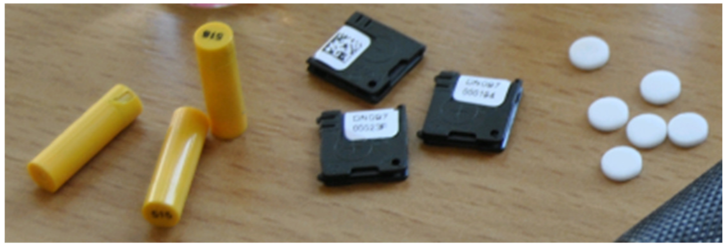




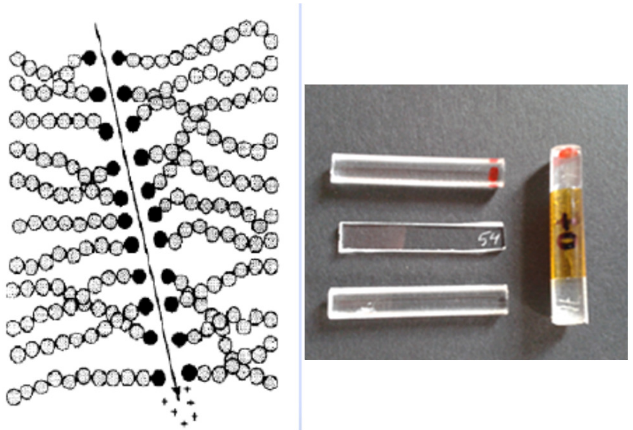
Agnieszka Wochnik et al 2020 Phys. Med. Biol. in press https://doi.org/10.1088/1361-6560/abcb1f

Dosimetry methods for out-of-field in-phantom measurements

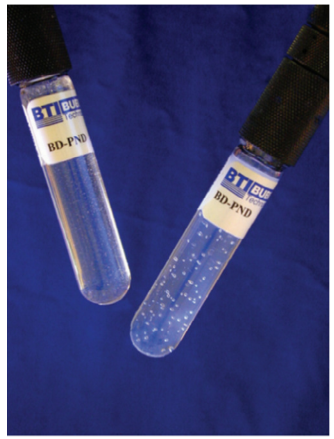
- Detectors
  - linear dose response **(mGy to Gy)**
  - **low energy dependence**
  - tissue equivalent, long term stability, reproducibility, mechanically strong, batch homogeneity
- Phantoms
  - Water tank – simple geometry
  - Anthropomorphic – clinical scenario



RPL *OSL* *TLD*



PADAC track detectors



Bubble detectors

Dosimetry methods for out-of-field in-phantom measurements

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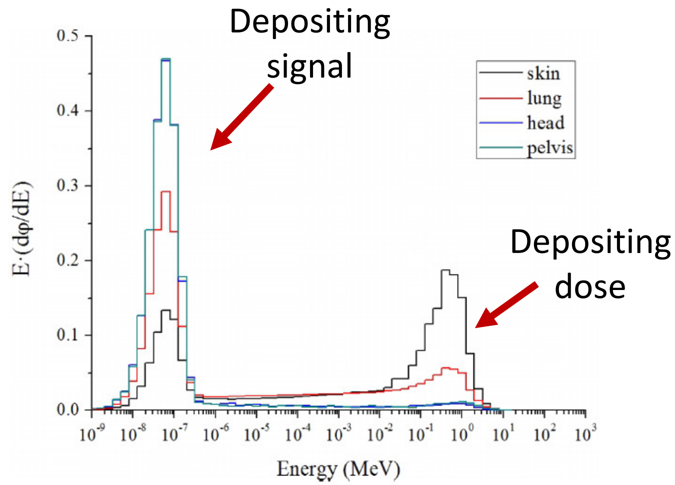
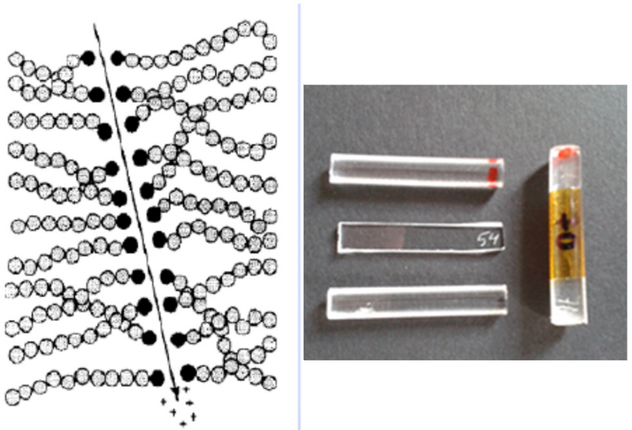
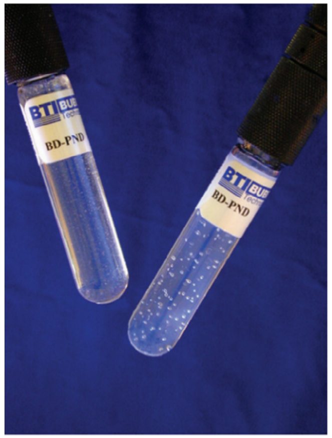


Romero-Exposito et al. Experimental evaluation of neutron dose in radiotherapy patients: Which dose? Med Phys 43 (2016) e391-e429



PADAC track detectors with measure thermal and high energy neutrons, converters



Bubble detectors

Dosimetry methods for out-of-field in-phantom measurements

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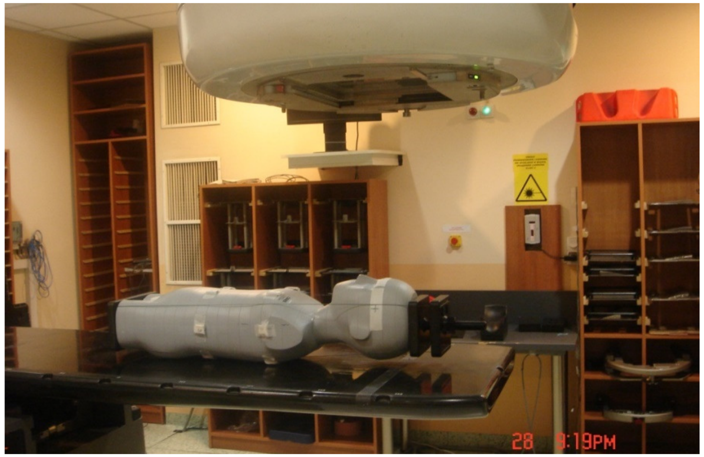
  - Anthropomorphic – clinical scenario

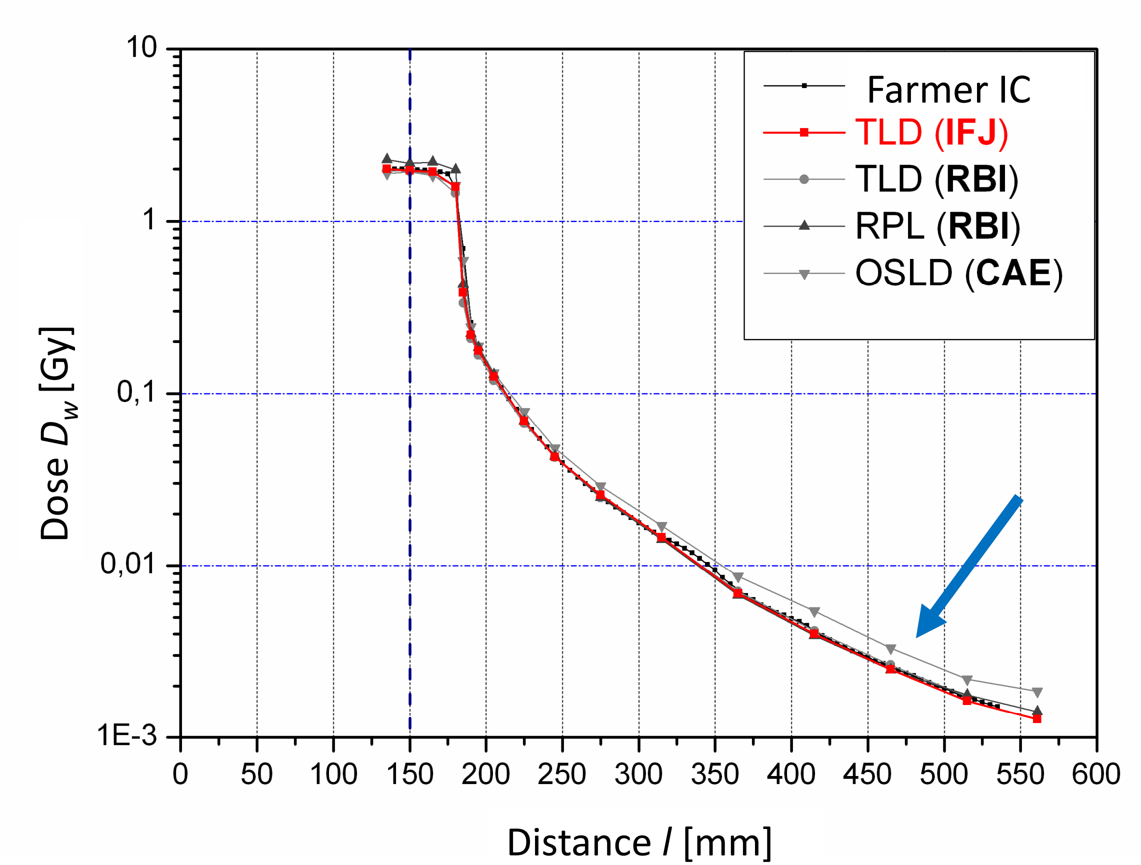
Water tank

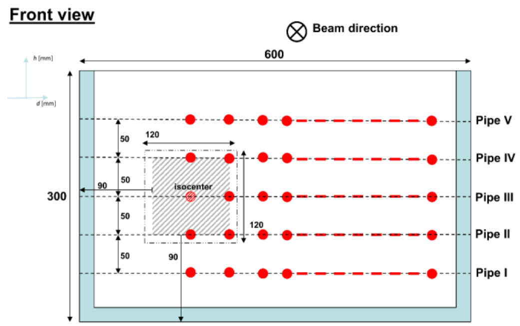
BOMAP type phantom

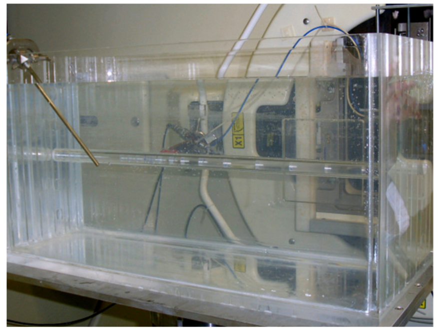


CIRS anthropomorphic phantom

Comparison of dosimetry systems in the scattered radiation field in photon radiotherapy



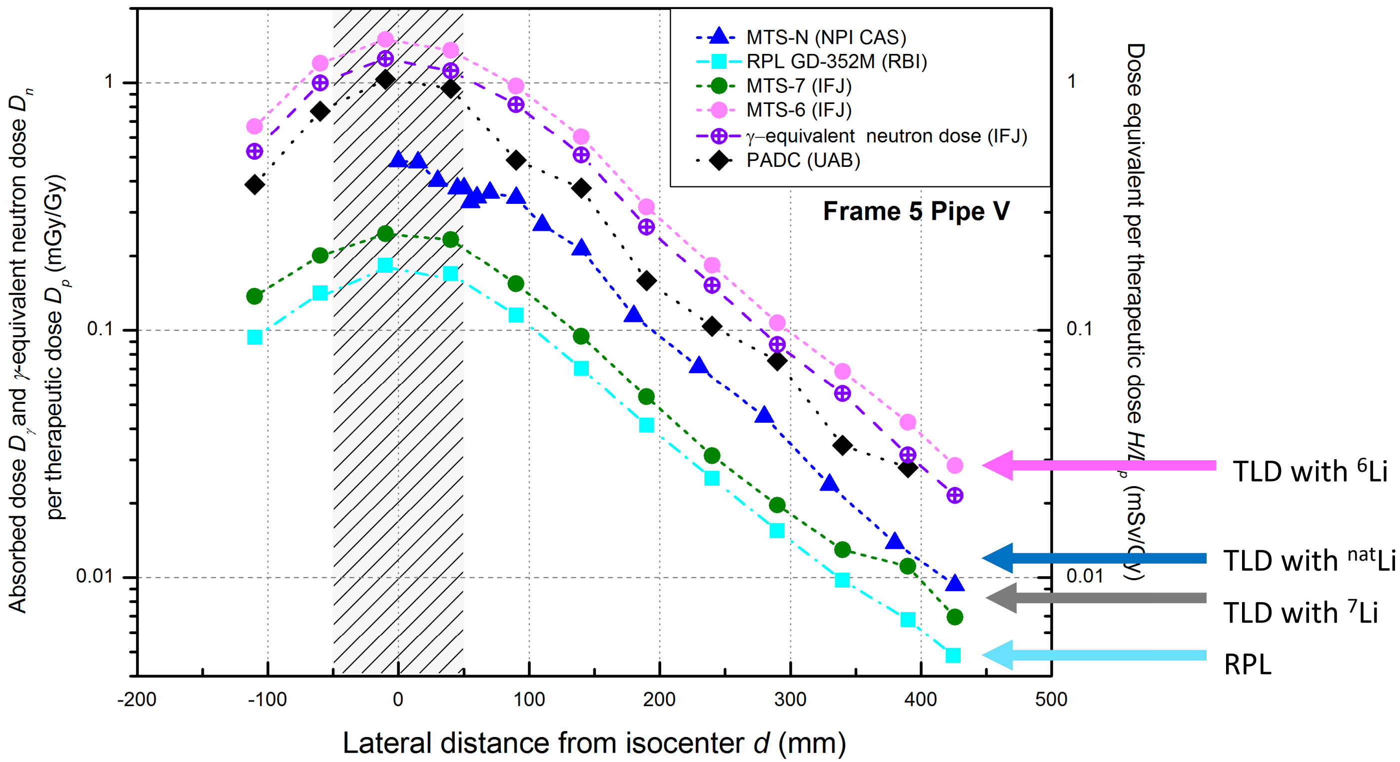


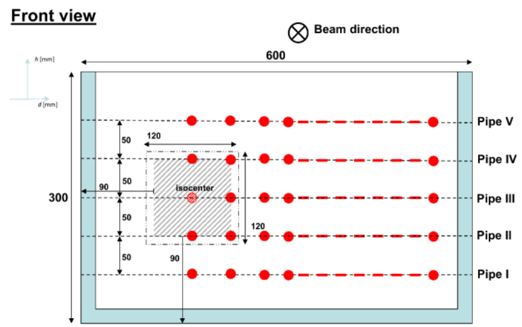


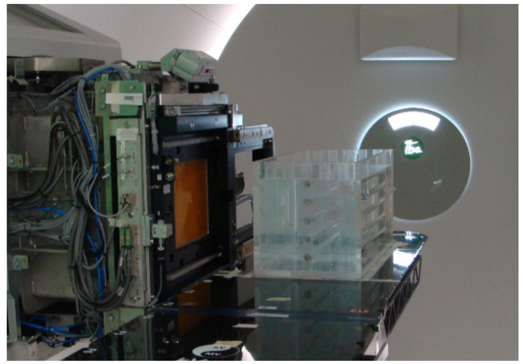
CEA, Saclay

J.M. Bordy, I. Bessieres, E. d'Agostino, C. Domingo, F. d'Errico, A. di Fulvio, Z. Knezevic, S. Miljanic, P. Olko, A. Ostrowsky, B. Poumarede, S. Sorel, L. Stolarczyk, D. Vermesse, Radiotherapy out-of-field dosimetry: Experimental and computational results for photons in a water tank. Radiation Measurements 57 (2013) 29-34

Comparison of dosimetry systems in the secondary radiation field in proton PBS radiotherapy







ATreP, Trento

Stolarczyk L, Trinkl S, Romero-Expósito M, Mojżeszek N, Ambrozova I, Domingo C, Davídková M, Farah J, Kłodowska M, Knežević Ž, Liszka M, Majer M, Miljanić S, Ploc O, Schwarz M, Harrison RM, Olko P., Dose distribution of secondary radiation in a water phantom for a proton pencil beam-EURADOS WG9 intercomparison exercise. Phys Med Biol. 2018 Apr 19;63(8):085017. doi: 10.1088/1361-6560/aab469.

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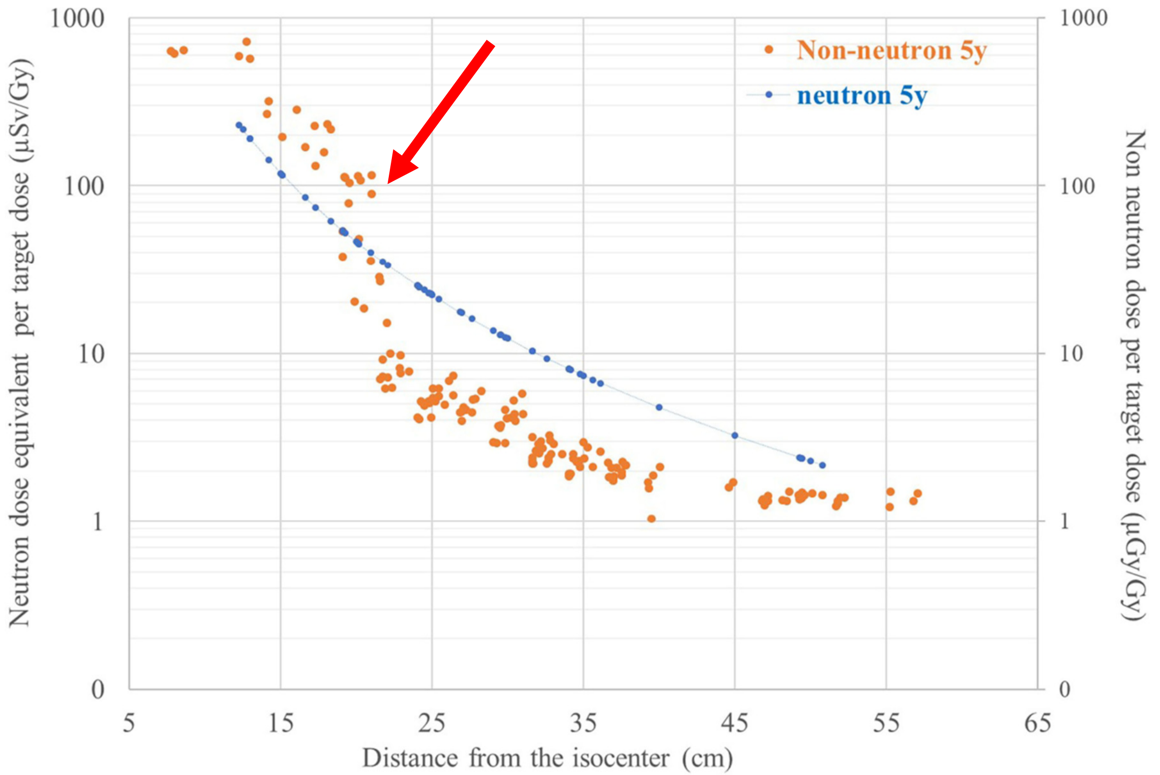
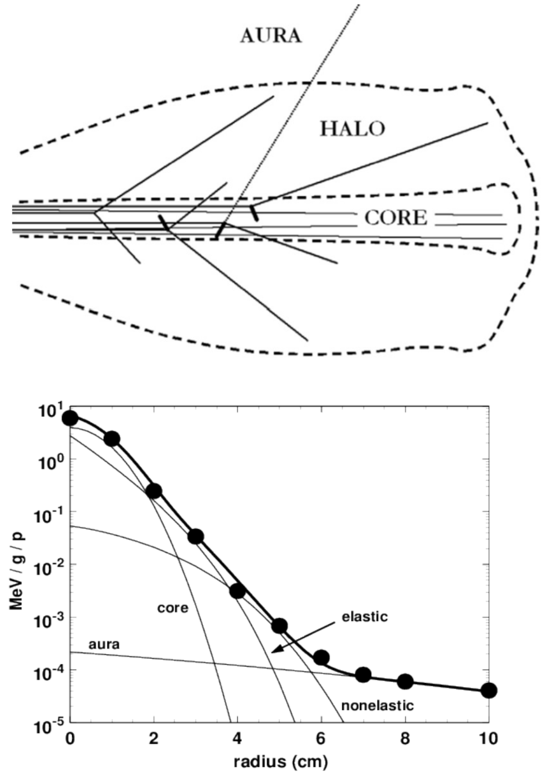
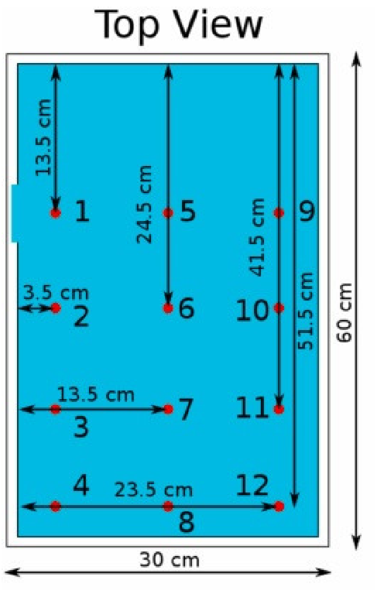


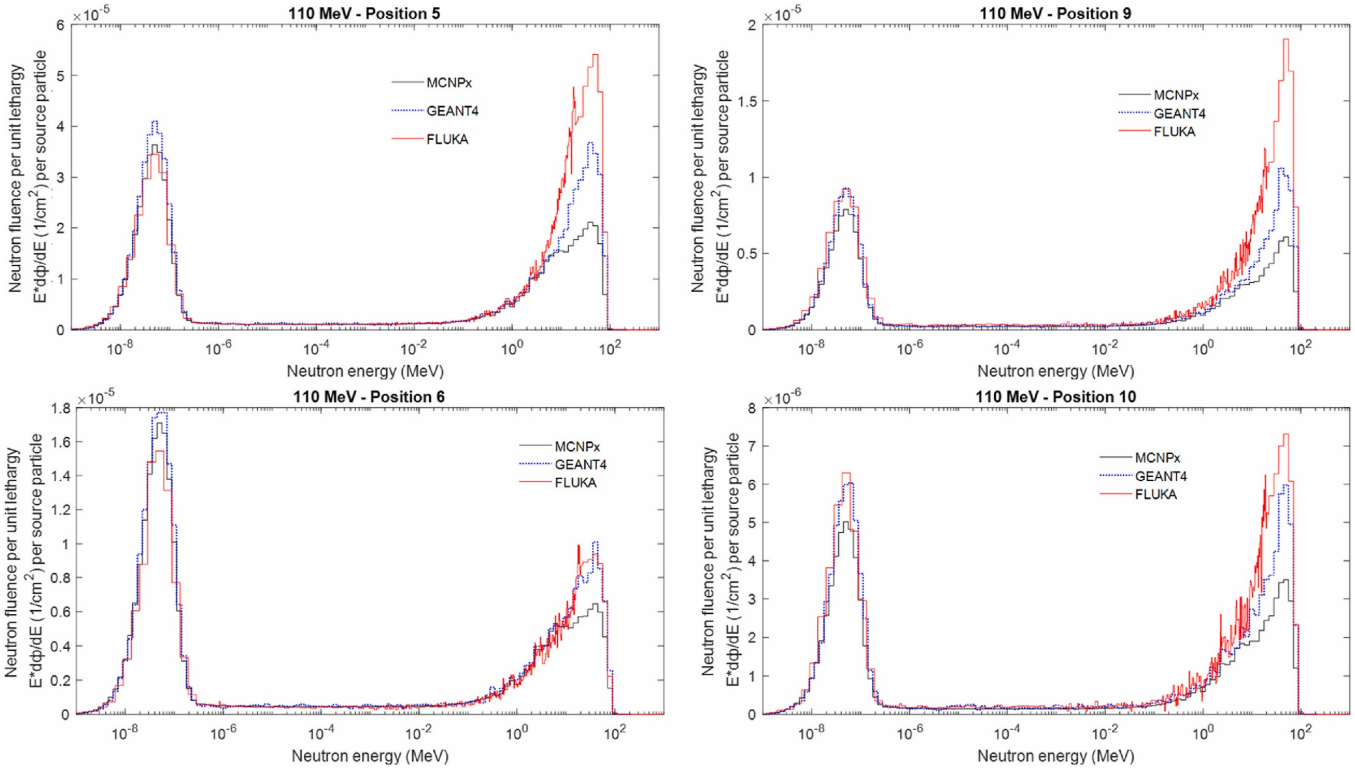


B. Gottschalk, E.W. Cascio, J. Daartz, and M.S. Wagner, "On the nuclear halo of a proton pencil beam stopping in water.," Phys. Med. Biol. **60**(14), 5627–5654 (2015)

Knežević, Željka, Liliana Stolarczyk, Iva Ambrožová, Miguel Á. Caballero-Pacheco, Marie Davídková, De Saint-Hubert, Carles Domingo et al. "Out-of-field doses produced by a proton scanning beam inside pediatric anthropomorphic phantoms and their comparison with different photon modalities." Frontiers in Oncology 12 (2022): 904563.

Secondary radiation doses – experimental benchmarking of MC codes





De Saint-Hubert, M., Farah, J., Klodowska, M., Romero-Expósito, M. T., Tyminska, K., Mares, V., ... & Trinkl, S. (2022). The influence of nuclear models and Monte Carlo radiation transport codes on stray neutron dose estimations in proton therapy. Radiation Measurements, 150, 106693.

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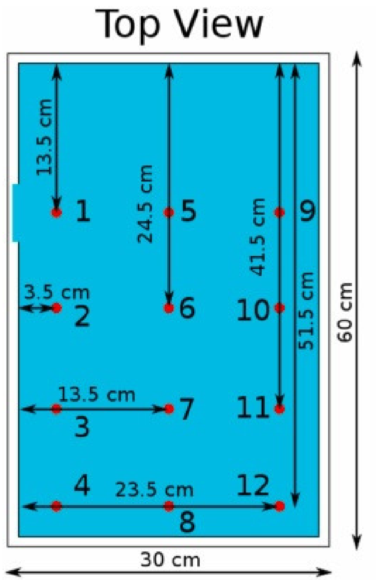


Average values of neutron dose equivalent from different MC codes (top) and variation of the neutron dose equivalent calculated from spectra simulated with different codes (bottom) in distal positions 5 and 9 and lateral positions 2, 6 and 10 for 110 MeV, 150 MeV, 180 MeV and 210 MeV proton beams.

Average neutron dose equivalent [mSv per source particle]				
Position	110 MeV	150 MeV	180 MeV	210 MeV
5	4.31E-11	IF	IF	IF
9	1.14E-11	4.06E-11	9.76E-11	IF
2	9.74E-12	1.40E-11	1.62E-11	1.75E-11
6	1.13E-11	2.35E-11	3.15E-11	3.73E-11
10	5.95E-12	1.68E-11	2.78E-11	4.11E-11
Variation (%) of neutron dose equivalent between codes				
Position	110 MeV	150 MeV	180 MeV	210 MeV
5	34	IF	IF	IF
9	45	32	25	IF
2	19	24	25	21
6	12	5	13	15
10	30	16	7	5

IF: in field point

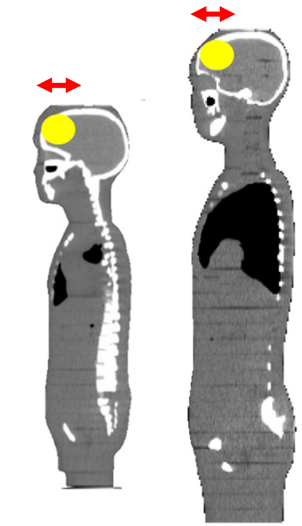
De Saint-Hubert, M., Farah, J., Klodowska, M., Romero-Expósito, M. T., Tyminska, K., Mares, V., ... & Trinkl, S. (2022). The influence of nuclear models and Monte Carlo radiation transport codes on stray neutron dose estimations in proton therapy. Radiation Measurements, 150, 106693.

Secondary radiation doses in paediatric patients

- Clinically relevant targets:
  - Brain tumour
  - Craniospinal irradiations
- Photon radiotherapy
  - 3D-CRT
  - IMRT
  - GammaKnife
  - VMAT
- Proton Pencil Beam Scanning
  - Facility with cyclotron and gantry
  - Facility with synchrocyclotron mounted on a gantry

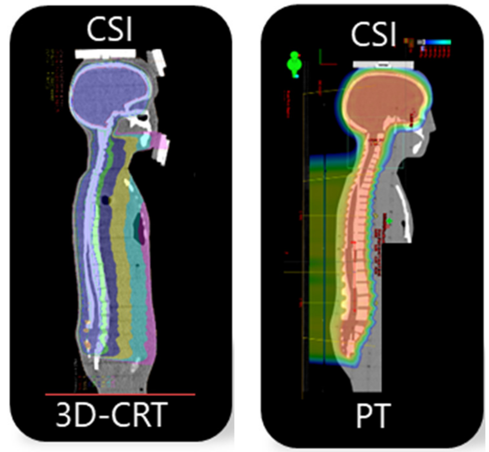
Brain tumour

PTV – 6 cm diam.

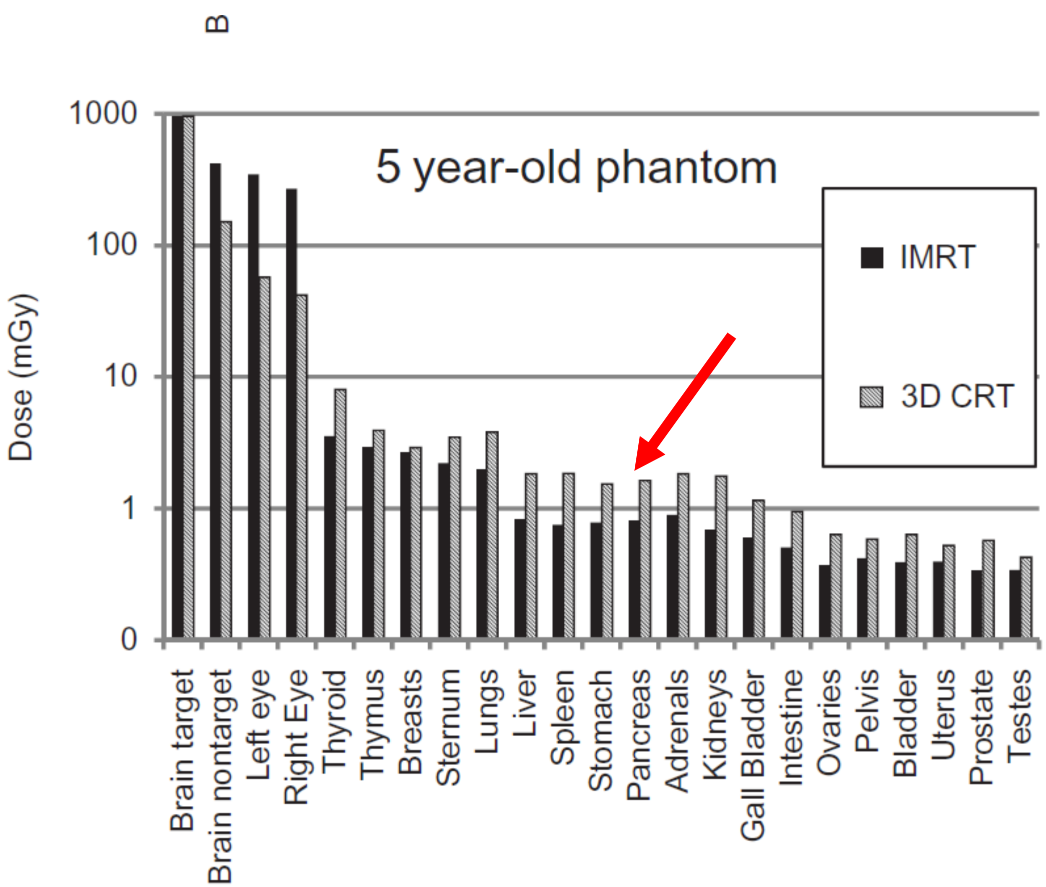


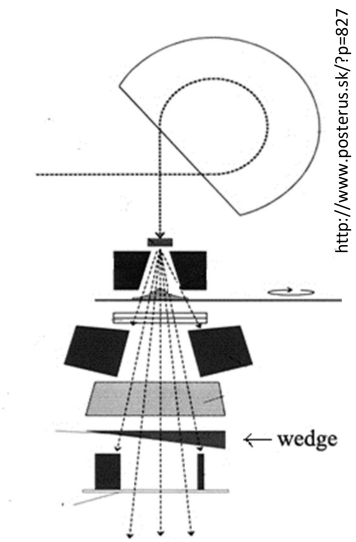
5 y 10 y

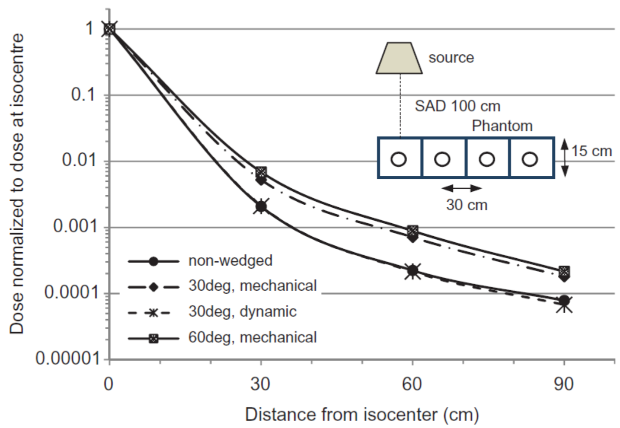
Craniospinal irradiations



Beam modifiers (3D CRT vs IMRT)

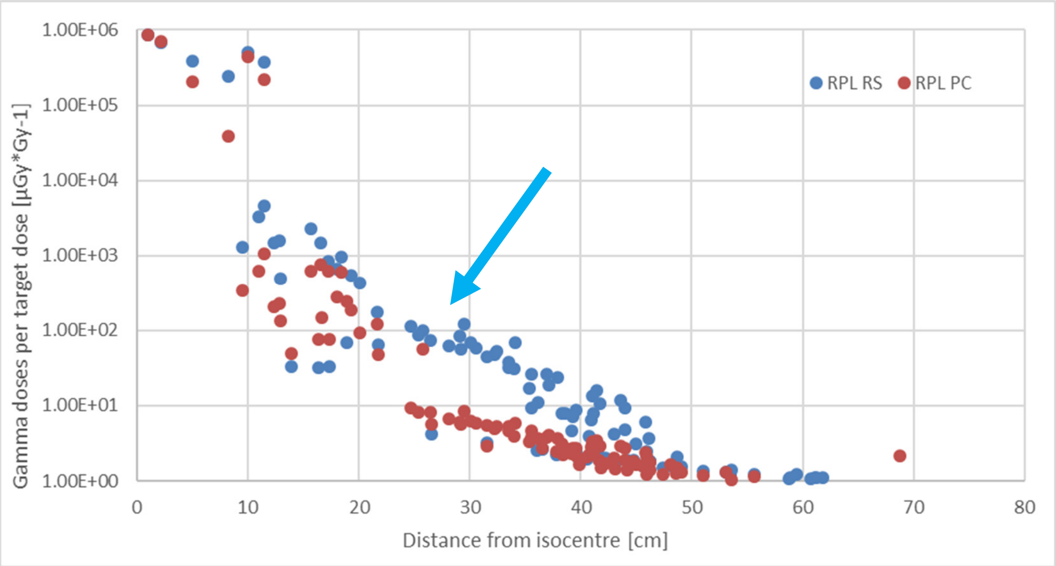


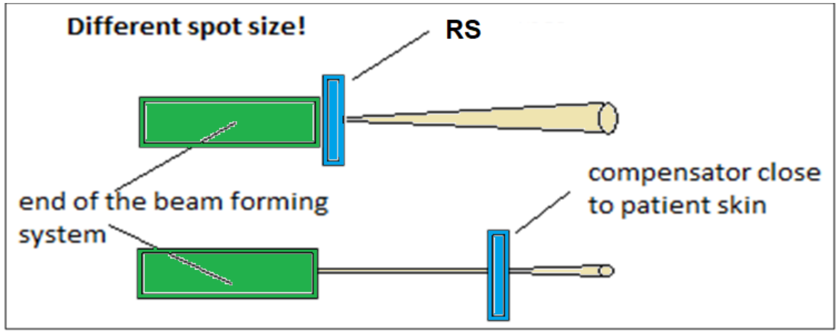


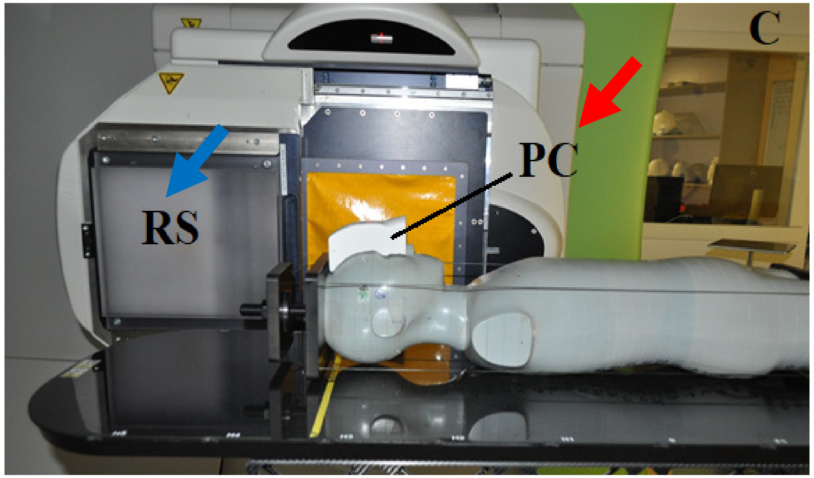


Majer M., Stolarczyk L., De Saint-Hubert M., Kabat D., Kneževic Z., Miljanic S., Mojzeszek N, Harrison R.. (RPD 2017) Out-of-field dose measurements for 3D-CRT and IMRT of a paediatric brain tumor.

Beam modifiers (proton spot scanning)

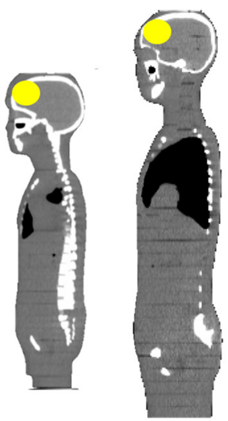




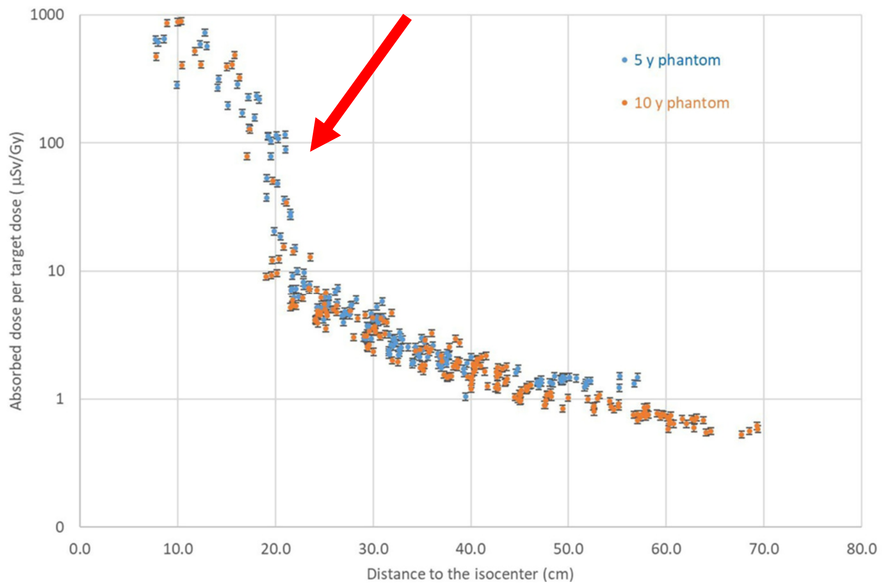


Wochnik, Agnieszka, Liliana Stolarczyk, I. Ambrožová, Marie Davidkova, Marijke De Saint-Hubert, Szymon Domański, Carles Domingo et al. "Out-of-field doses for scanning proton radiotherapy of shallowly located paediatric tumours—a comparison of range shifter and 3D printed compensator." Physics in Medicine & Biology 66, no. 3 (2021): 035012.)

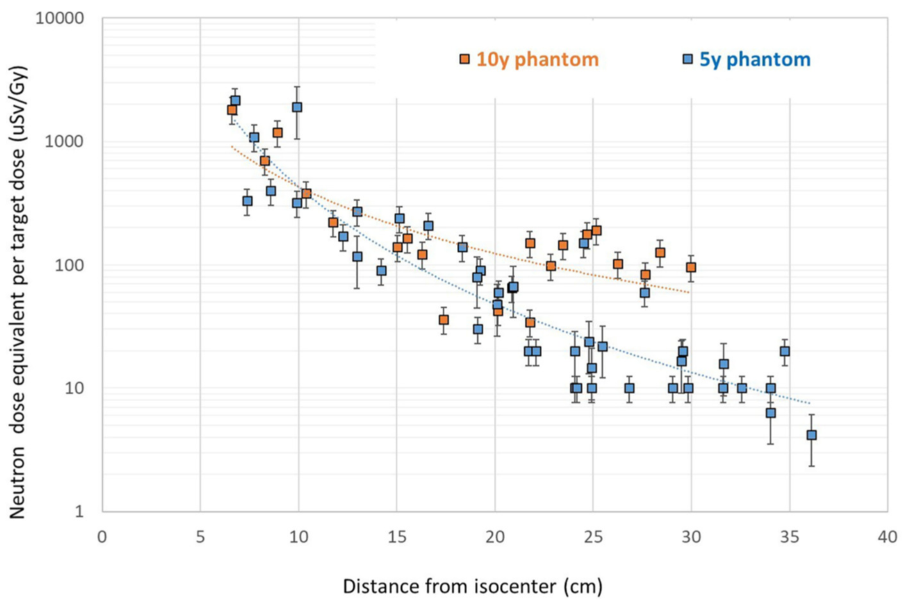
Phantom size (proton PBS)



Non-neutron doses (RPL detectors)

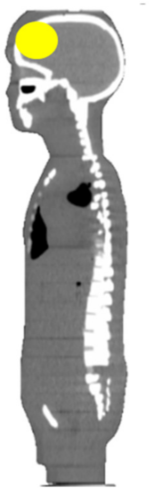


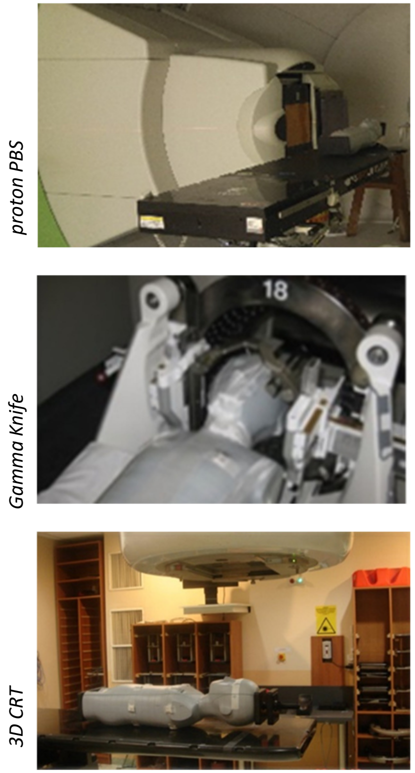
Neutron dose equivalent (PADC detectors)

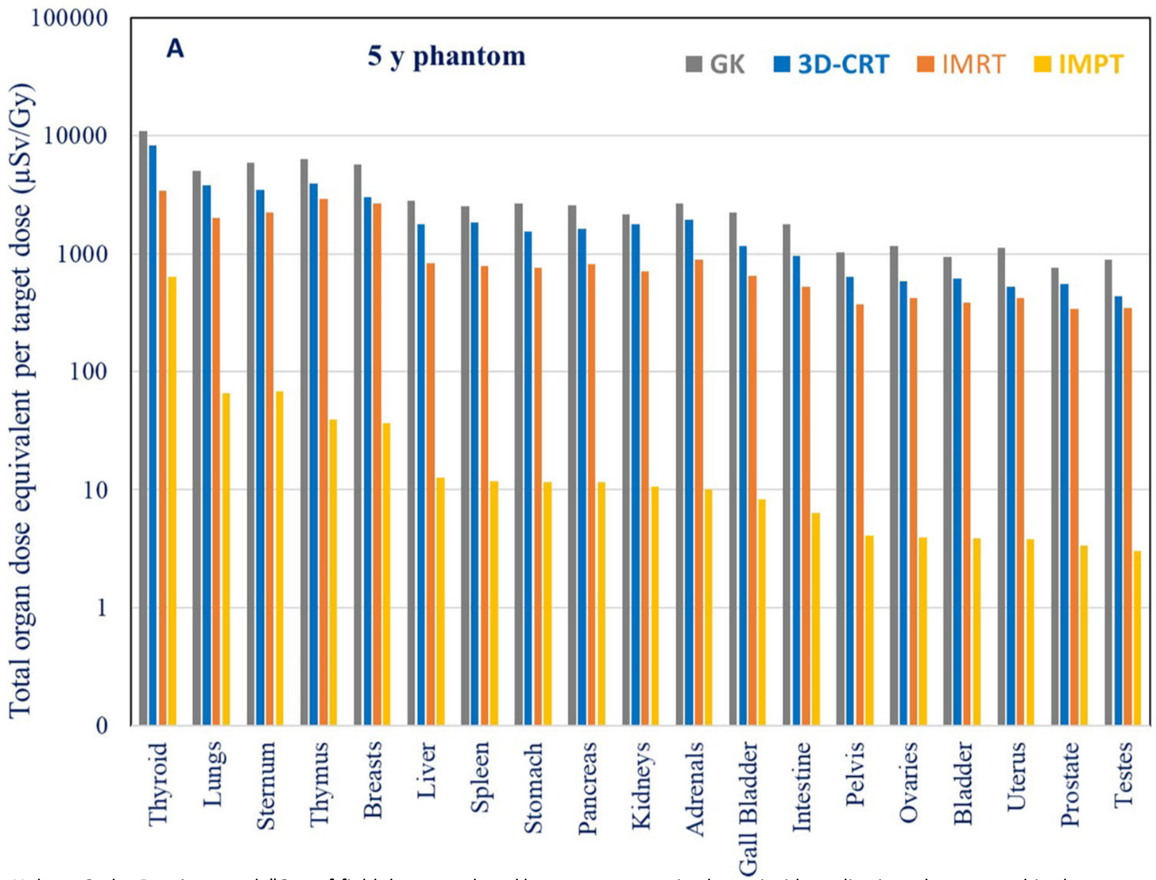


Knežević, Željka, Liliana Stolarczyk, Iva Ambrožová, Miguel Á. Caballero-Pacheco, Marie Davídková, De Saint-Hubert, Carles Domingo et al. "Out-of-field doses produced by a proton scanning beam inside pediatric anthropomorphic phantoms and their comparison with different photon modalities." Frontiers in Oncology 12 (2022): 904563.

Secondary radiation doses in paediatric patients (brain tumour)

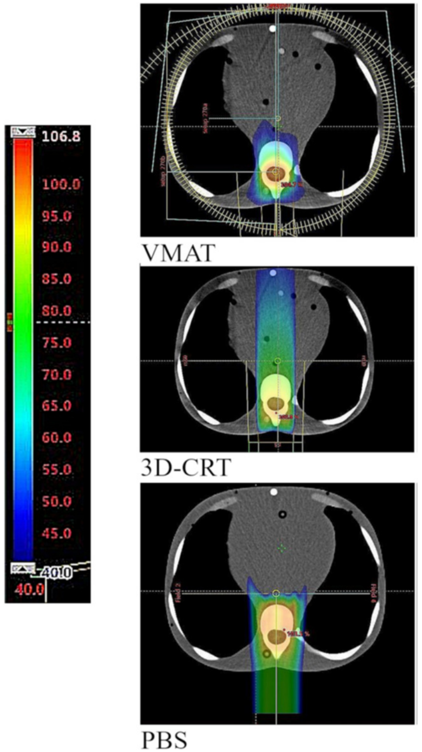


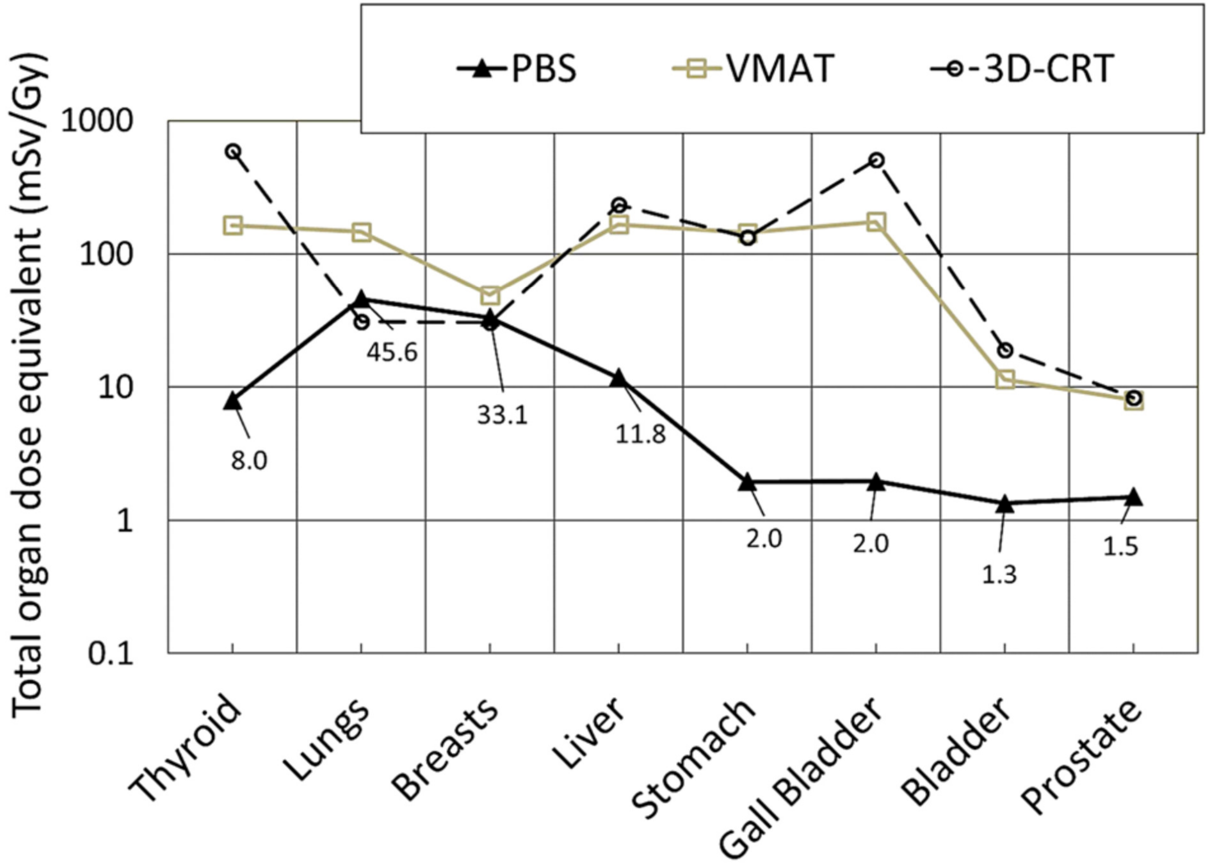




Knežević, Željka, Liliana Stolarczyk, Iva Ambrožová, Miguel Á. Caballero-Pacheco, Marie Davídková, De Saint-Hubert, Carles Domingo et al. "Out-of-field doses produced by a proton scanning beam inside pediatric anthropomorphic phantoms and their comparison with different photon modalities." Frontiers in Oncology 12 (2022): 904563.

Secondary radiation doses in paediatric patients (CSI)





Majer, Marija, Iva Ambrožová, Marie Davídková, Marijke De Saint-Hubert, Mladen Kasabašić, Željka Knežević, Renata Kopeć et al. "Out-of-field doses in pediatric craniospinal irradiations with 3D-CRT, VMAT, and scanning proton radiotherapy: A phantom study." Medical Physics 49, no. 4 (2022): 2672-2683..

Radiotherapy during pregnancy

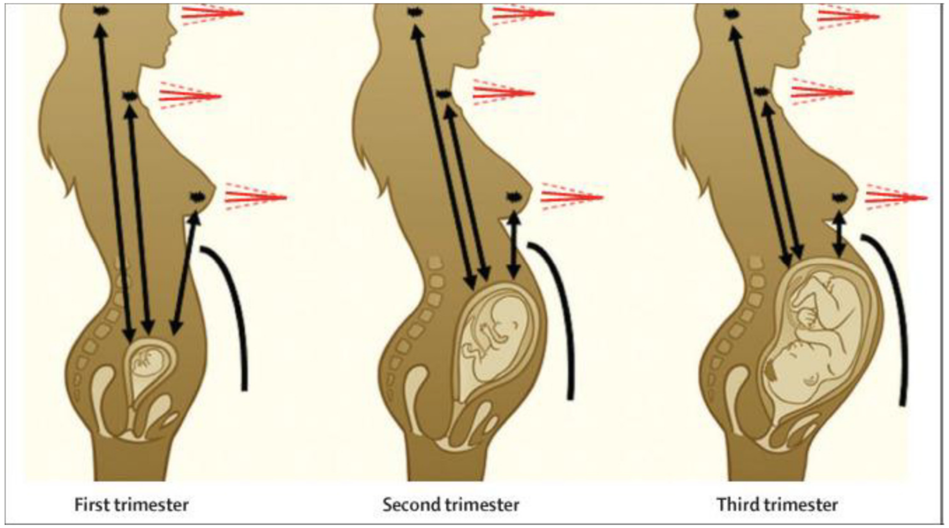
- **1 in 1000 pregnancies** is complicated with cancer
- More than 70% of patients are treated during pregnancy
- Radiotherapy is only applied in **3% of the cases**
- Mostly breast (54%) and brain cancers (15%)
- In first trimester can be an alternative to chemotherapy avoiding treatment delays
- Generally radiotherapy is postponed till after delivery

Stage of pregnancy	Therapeutic options
First trimester	Surgery
	Radiotherapy
Second trimester	Surgery
	Radiotherapy
	Chemotherapy
Third trimester	Surgery
	Chemotherapy

F. Amant, et al., European Journal of Cancer 2010

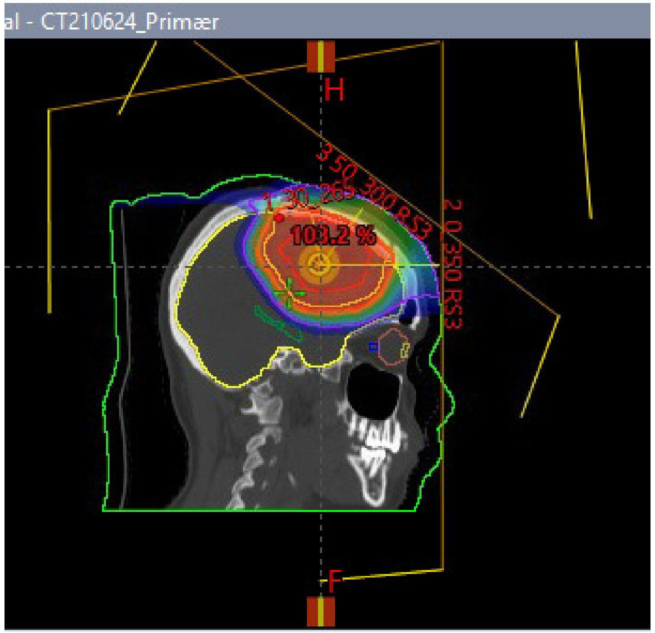
Risk of fetal damage

- Lack of reliable information on the risk of fetal damage
- Lack of data on the dose to the fetus during pregnancy
- What dose is allowed?
    - ICRP-Threshold for deterministic effects (e.g. malformations) 100-200 mGy
    - Generally a threshold of **100 mGy** is used
    - ICRP-Embryo doses of **10 mGy** may increase the risk of cancer to 40% over normal incidence
- **Proton pencil beam scanning (PBS)** could reduce the dose to fetus up to more than **a factor of 10**



T Vandenbroucke, et al. The Lancet 2017. Effects of cancer treatment during pregnancy on fetal and child development

Fetus doses in proton PBS therapy



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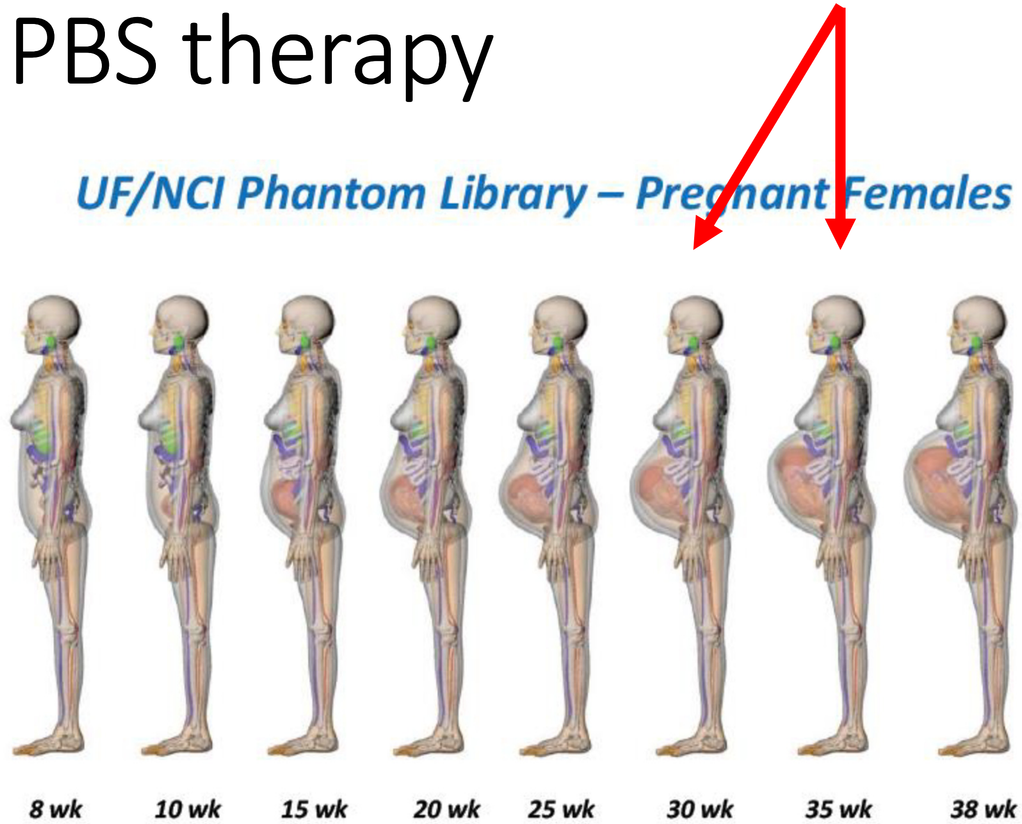

The UF Family of hybrid phantoms of the pregnant female for computational radiation dosimetry

Phys. Med. Biol. 59 (2014) 4325–4343

Matthew R Maynard[1], Nelia S Long[1], Nash S Moawad[2], Roger Y Shifrin[3], Amy M Geyer[1], Grant Fong[4] and Wesley E Bolch[1,5]

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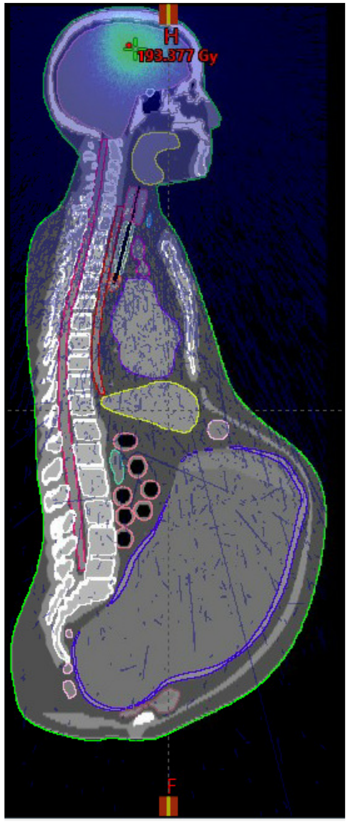
Fetus doses in proton PBS therapy



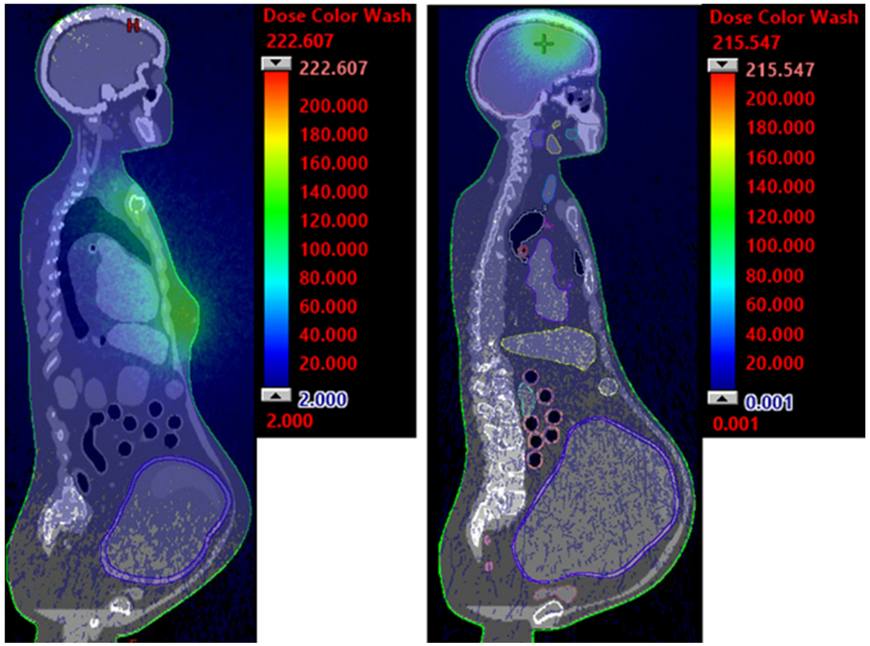
Uterus Mean H*(10) [mSv]
(33 fractions / 59.4Gy)

	Phantom 30wk	Phantom 35wk
F1	0.05 mSv	0.05 mSv
F2	0.08 mSv	0.08 mSv
F3	0.15 mSv	0.16 mSv
Sum	**0.27 mSv**	**0.29 mSv**

(from measurements 0.6 mSv)

Stolarczyk et al., Neutron dose estimation for a foetus from proton pencil beam scanning radiotherapy of brain and breast targetsnt J Part Ther. 2023 Spring; 9(4): 306–470

Fetus doses in proton and photon therapy



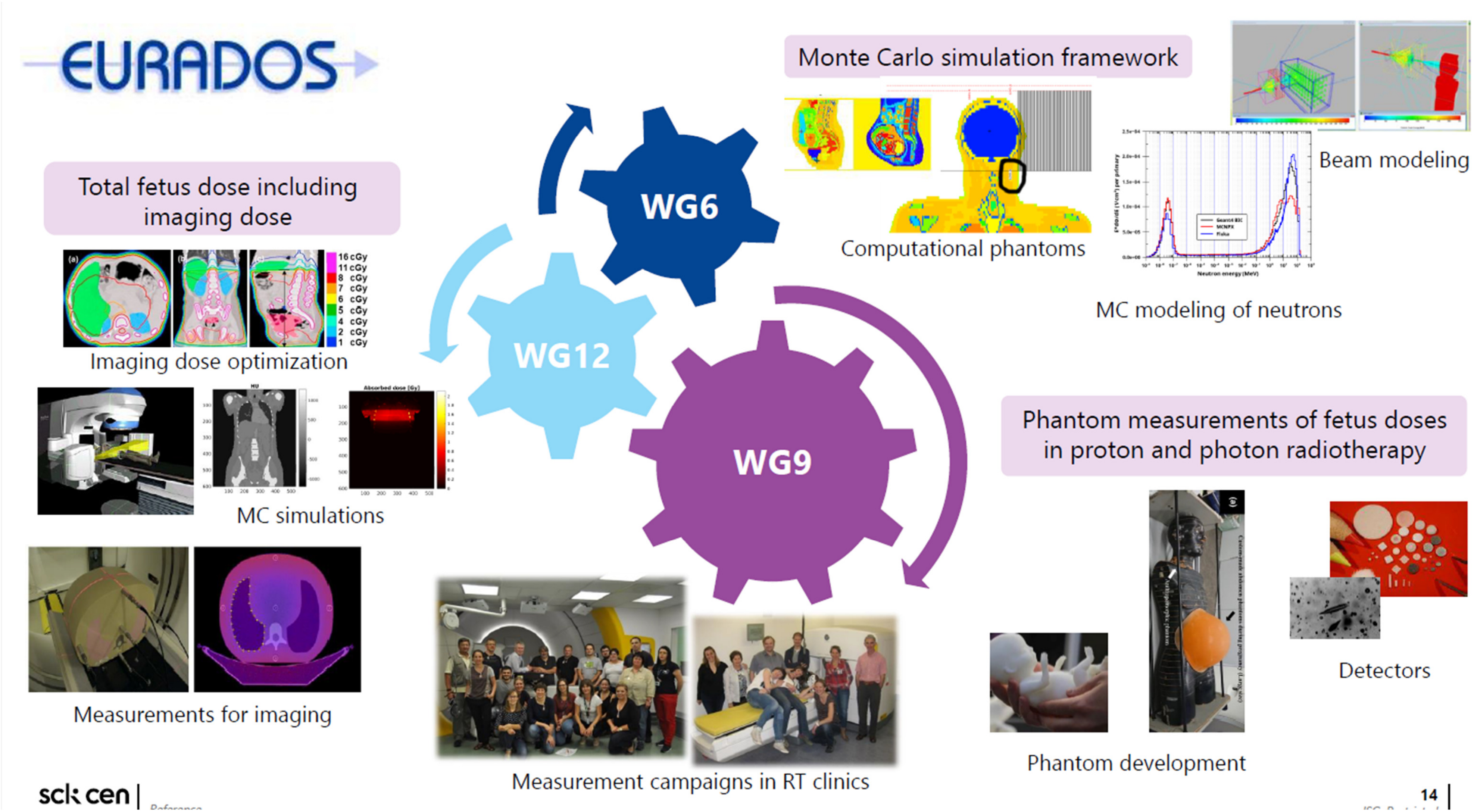
Neutron H*(10) [mSv] distribution simulated in TOPAS, and presented in Eclipse, for a 50 degree field of the breast plan (left) and a 300 degree field of the brain plan (right).

Dose to foetus

Proton radiotherapy of a brain target	**0.3 mSv**
Proton radiotherapy of a breast target	**12 mSv**
Photon radiotherapy of a brain target [1]	7 – 42 mGy
Photon radiotherapy of a breast target [2]	40 – 180 mGy
Threshold of embryo doses (increased risk of cancer)	10 mGy
Threshold for deterministic effects (e.g. malformations)	100 mGy

[1] Radiat Oncol 16,109 (2021)
[2] Crit Rev Onco/Hema 136, 13–19 (2019)

Stolarczyk et al., Neutron dose estimation for a foetus from proton pencil beam scanning radiotherapy of brain and breast targetsnt J Part Ther. 2023 Spring; 9(4): 306–470

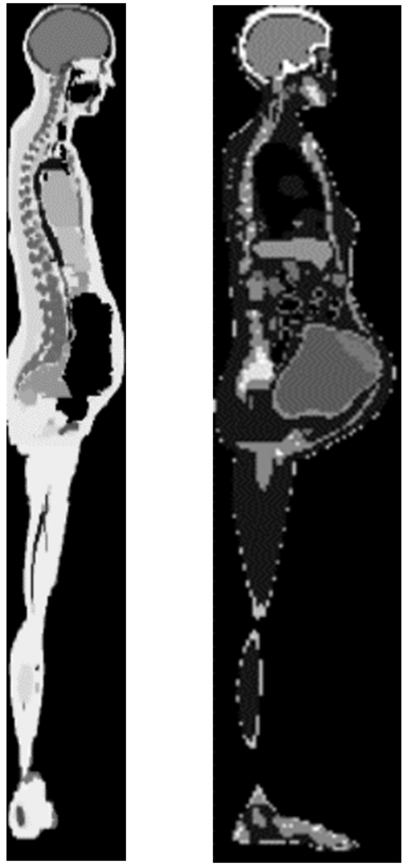


courtesy of Marijke De Saint-Hubert (SCK CEN)

Monte Carlo simulation framework

- The result obtained for two different phantoms differs, possibly due to the positioning of the fetus and the geometrical characteristics of the mother
  - Compared to UF 25, Katja is thinner
  - Head position
  - Fetus position is different (in Katja fetus is in a more cranial position)

Katja UF 25



M. De Saint-Hubert, et al. Rad Meas 2021. Fetus dose calculation during proton therapy of pregnant phantoms using MCNPX and MCNP6.2 codes

Monte Carlo simulation framework

- Result obtained by two different phantoms differ possible due to the **positioning of the fetus** and the **geometrical characteristics** of the mother
  - Compared to UF 25, Katja is thinner
  - Head position
  - Fetus position is different (in Katja fetus is in a more cranial position)

	Dose quantities			Difference to Katja (%)	
	Katja	UF20	UF25	UF20	UF25
Photon dose per target dose [nGy/Gy]	108	60	64	44%	40%
Neutron dose equivalent per target dose [nSv/Gy]	672	295	332	56%	51%
Total dose equivalent per target dose [nSv/Gy]	780	355	396	54%	49%

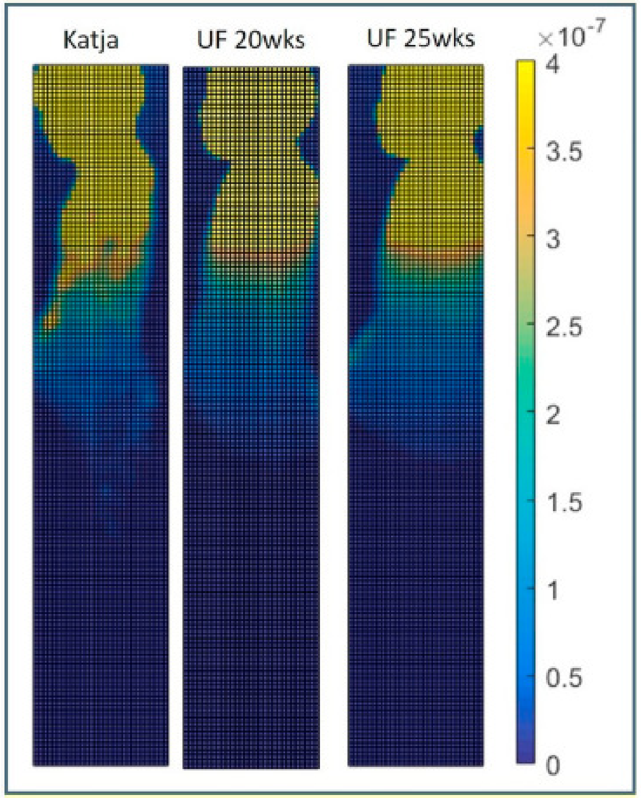


Fig. 3. Image of the mesh tally the total absorbed dose through the phantom. Results from Group 1 are shown for Katja, UF20 and UF25.

M. De Saint-Hubert, et al. Rad Meas 2021. Fetus dose calculation during proton therapy of pregnant phantoms using MCNPX and MCNP6.2 codes

Development of a pregnant female phantom (TENA)

- Second trimester (17 weeks)
  - Voxelized + MESH + DICOM
  - Physical phantom
- 5 cm tick slices – with inserts to hold detectors + 3D printed molds
- 3 mixtures
  - Bones - Epoxy wax (60 %) + Si02 (5%) + CaCO3 (30 %)
  - Soft tissue – polyurethane rubber (PU) 97.2 % + 2,8% CaCO3
  - Lungs - Soft tissue mixture (92.6 %) +polystyrene (7.4 %)
- Validated in photon breast radiotherapy
- Ongoing validation in proton BPS

courtesy of Marijke De Saint-Hubert (SCK CEN) and Hrvoje Brkic (UoO)

Kopacin, Vjekoslav, Mladen Kasabasic, Dario Faj, Marijke de Saint Hubert, Stipe Galic, Ana Ivkovic, Marija Majer, and Hrvoje Brkic. "Development of a computational pregnant female phantom and calculation of fetal dose during a photon breast radiotherapy." Radiology and Oncology 56, no. 4 (2022): 541-551.

Conclusions

- Treatment planning systems are still not suitable for calculating non-target doses
- Analytical models and MC simulations require validation vs measurements (neutrons!)
- Beam modifiers can increase out-of-field doses by up to a factor of 2
- Normalization of out-of-field doses to the target dose is meaningful only when the properties of the primary field are known.
- Proton pencil beam scanning (PBS) therapy reduces out-of-field doses in children by up to two orders of magnitude compared to photon RT techniques
- The dose to a fetus for proton PBS radiotherapy is considerably lower than for photon radiotherapy.

Thank you for your attention

European Radiation Dosimetry Group

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