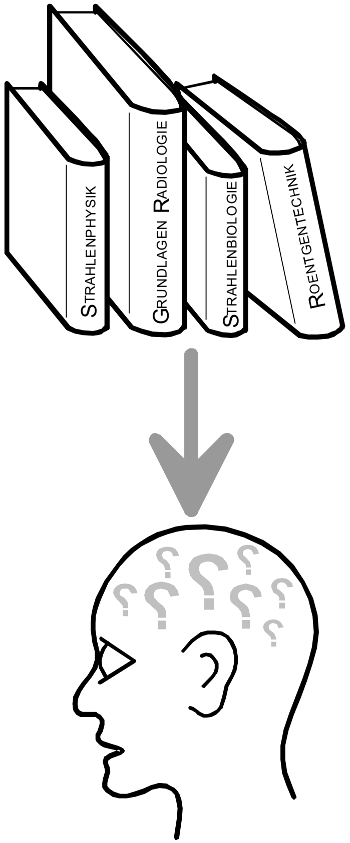
SGSMP Physics Course for FMH residents

Radiation Protection

Lecture by
Prof. Dr. Uwe Schneider

Contents


STRAHLENPHYSIK
GRUNDLAGEN RADIOLOGIE
STRAHLENBIOLOGIE
ROENTGENTECHNIK

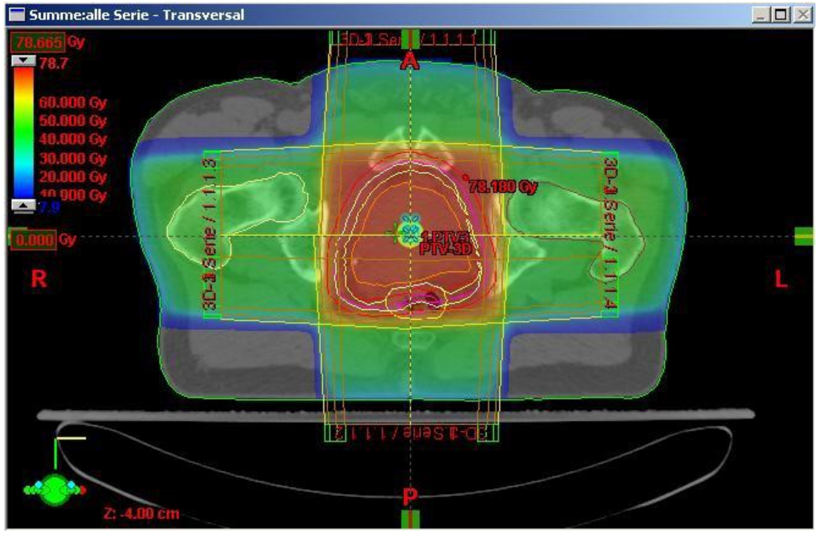
TEXTBOOKS

Philipp R. Trueb
Kompendium für ärztliche Strahlenschutz-Sachverständige

Content

- Radiation effects
- Dose definition and dose measurement
- Radiation exposure
- Radiation damage
- Radiation risk and cancer induction
- Natural radiation
- Artificial radiation

Measurement of dose I



Radiotherapy:

Requires a quantitative concept of a ‘dose of radiation’ for a patient:

- to predict associated radiation effects (radiation detriments)
- to reproduce clinical outcomes.

Radiation protection:

requires quantitative methods to determine a ‘dose of radiation’ for a person:

- to protect the employees

Absorbed dose

- The interactions of radiations with atoms result in the transfer of energy from the particles to the medium
- The energy loss per unit mass is called the dose

  1 Joule / kilogram = 1 Gray (Gy)

- The energy loss has two consequences:

  it can heat up the medium (via vibration and rotation of molecules)

  it can damage the molecules of the medium

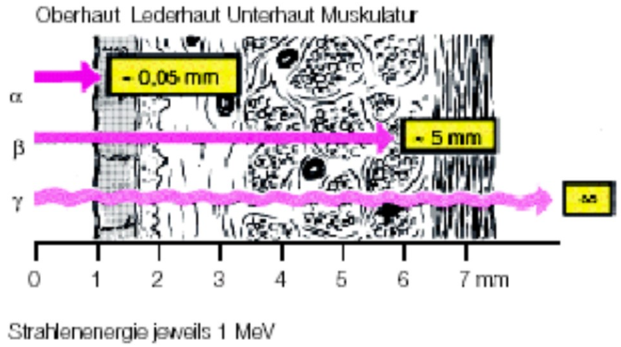
> 96% of energy appears as heat

Dose is merely a surrogate for what we care about – namely, biological effects

Effects of radiation exposure

How effective is radiation exposure?

-Radiation deposits energy in the body: in a confined volume dependent on radiation quality.

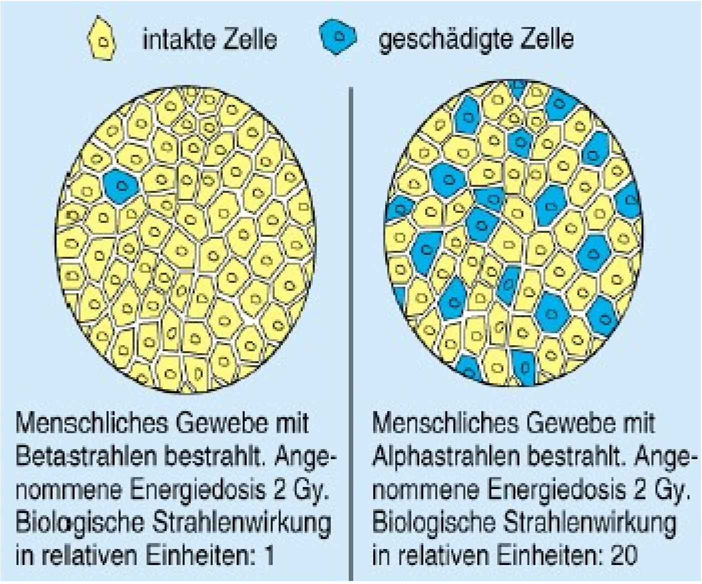


- This energy can be measured.

In the context of radiation it is true what PARACELSUS wrote:

"the dose makes the poison"

Measurement of dose II



Absorbed dose

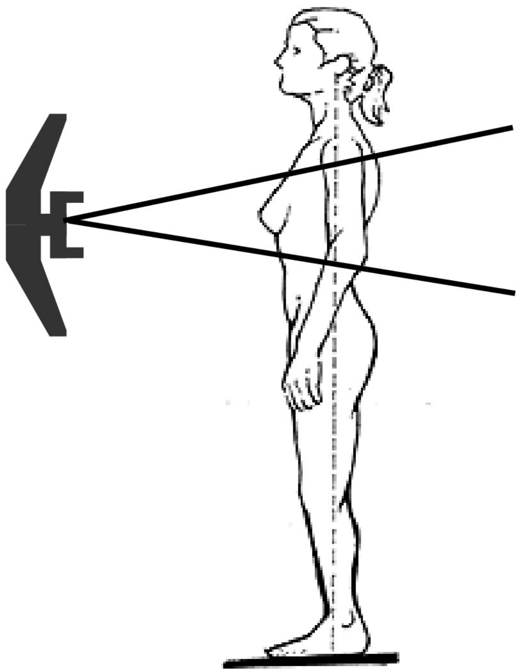
D = energy/mass [1 Joule/kg = 1 Gy]

can be measured, but:

- not accounted for biological effects
- different organ sensitivity (with regard to the same absorbed dose)
- absorbed dose is a point dose

Dose definition I

X-ray exposure:
0.1 Gy x 1 = 0.1 Sv



Neutron exposure:
0.1 Gy x 20 = 2 Sv

Equivalent dose

Accounts for the effectiveness of the given radiation in inducing biological harm:

$H_{T,R} = D_T \times w_R$ in Sievert (Sv)

D_T = absorbed dose in Gy
w_R = weighting factor for radiation quality

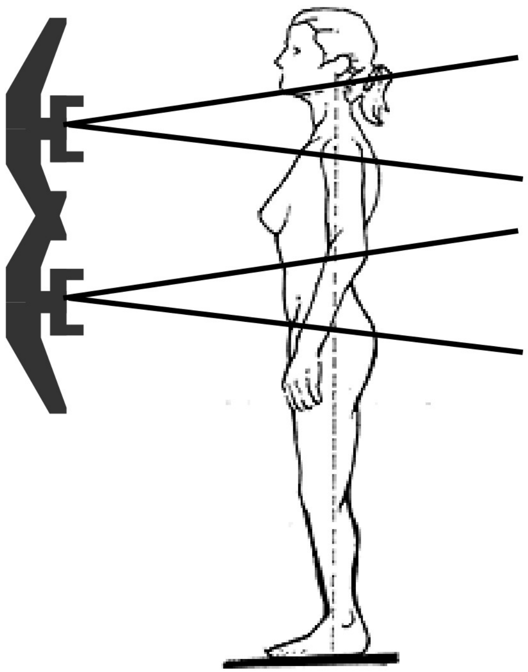
Dose definition II

Weighting factors (StSV Anhang 4; 1.4)

Radiation quality and energy		Weighting factor w_R
Photons, all energies		1
Electrons, all energies		1
Neutrons:	energy-range	
	- below 1 MeV	$2.5 + 18.2 \cdot e^{-(\ln(E))^2/6}$
	- 1 MeV - 50 MeV	$5.0 + 17.0 \cdot e^{-(\ln(2 \cdot E))^2/6}$
	- larger than 50 MeV	$2.5 + 3.25 \cdot e^{-(\ln(0.04 \cdot E))^2/6}$
Protons		2
Alpha-particles, heavy ions		20

Dose definition IV

Irradiation of thyroid:
0.1 Sv x 0.04 = 0.004 Sv



Irradiation of colon:
0.1 Sv x 0.12 = 0.012 Sv

Effective dose

Accounts for different organ sensitivities:

$E = \Sigma_T H_T \times w_T$ in Sievert (Sv)

H_T = Equivalent dose in tissue T
w_T = weighting factor for tissue T

Dose definition V

Weighting factors for different organs (StSV Anhang 4; 1.7)

Organ or tissue	Weighting factor w_T
Gonads	0.08
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.04
Breast	0.12

Organ or tissue	Weighting factor w_T
Liver	0.04
Esophagus	0.04
Thyroid	0.04
Brain	0.01
Skin	0.01
Bone surface	0.01
Salivary gland	0.01
Remainders	0.12

Dose limits I

Dose limits:

- Dose limits are defined for specific person groups
- Dose limits are not applicable to medical exposures
  - resulting from diagnostic procedures applied in diagnosis
  - therapeutic procedures applied in treatment of disease.
- Dose limits are not applicable to natural exposures
- Dose limits are defined by the Radiation Protection legislation (based on ICRP-report 60, 1990 and ICRP report 103, 2007)

Dose limits II

Annual dose limits from StSV (26.04.2017)

Group	**Location and dose quality**	**Dose limit in mSv/a**
Occupationally exposed to radiation	Effective dose	20
	Eye lens (Equivalent dose)	20
	Skin, hands, feet (Equivalent dose)	500
	Persons between 16 and 18 years of age (effective dose)	6
	Pregnant workers at abdomen (Equivalent dose)	1
Public exposure	Effective Dose (without environmental and medical exposure)	1
	Eye lens: Equivalent dose	15
	Skin: Equivalent dose	50

Radiation Exposure

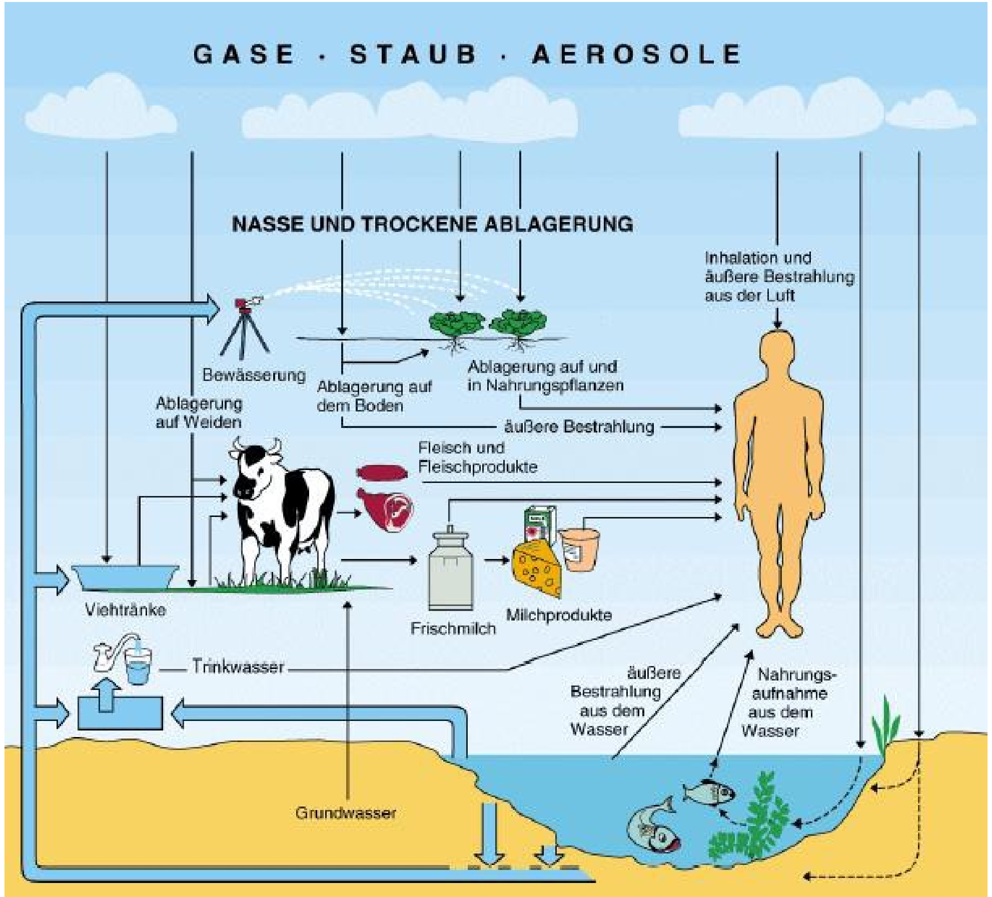
A radiation exposure is each event during which dose can be absorbed

Radiation exposure can happen by:

1. Irradiation from outside:
   Source is outside of the body or skin is contaminated.
2. Irradiation from inside:
   Source is gaseous, fluid or aerosol and be inhaled or eaten.

Radiation exposures are divided into three categories:

- Occupational exposure.
- Medical exposure.
- Public exposure.

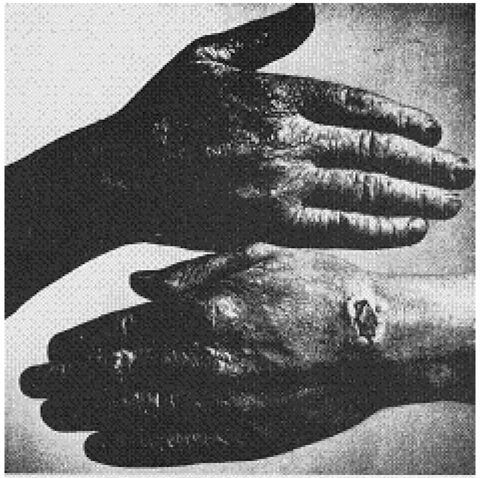


Radiation Injury

Deterministic effects

- Radiation injury at large dose: H>0.5 Sv
- Complication is a function of Equivalent dose and Volume
- Certain to occur above threshold level for dose

Stochastic effects



- Malignancies and hereditary effects
- Probability of tumor induction is function of effective dose

Deterministic effects

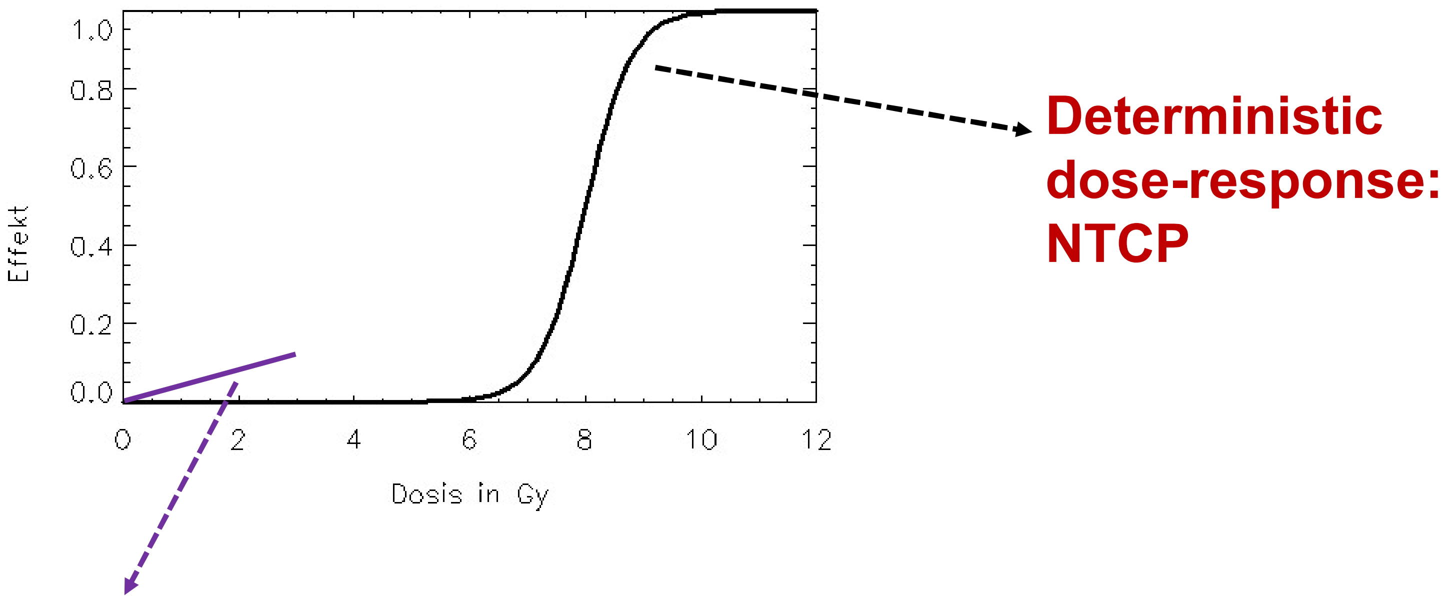
Lethal Dose LD50: 4 Sv

Organ	**Dosis $TD_{50/5}$* [Gy]**	**Dosis $TD_{5/5}$* [Gy]**	**Endpoint**
Kidney	28	23	Nephritis
Bladder	80	65	Bladder contracture
Skin	70	55	Necrosis/Ulceration
Optic nerve	65	50	Blindness
Eye lens	18	10	Cateract
Lung	24.5	17.5	Pneumonitis
Stomach	65	50	Ulceration/Perforation
Liver	40	30	Liver failure

*probability of 50% and 5% complication within 5 years, respectively

Data from Emami et al, Int J rad Onc Biol Phys 1991 21 109

Stochastic effects



Stochastic dose-response:

- No dose threshold; linear
- For radiation exposures far beyond the threshold dose
- stochastic effects is proportional to the effective dose
- Comparisons on the basis of effective dose:
  x-rays, Radiation-Oncology, natural exposures

Radiation risk

Estimation of radiation risk:

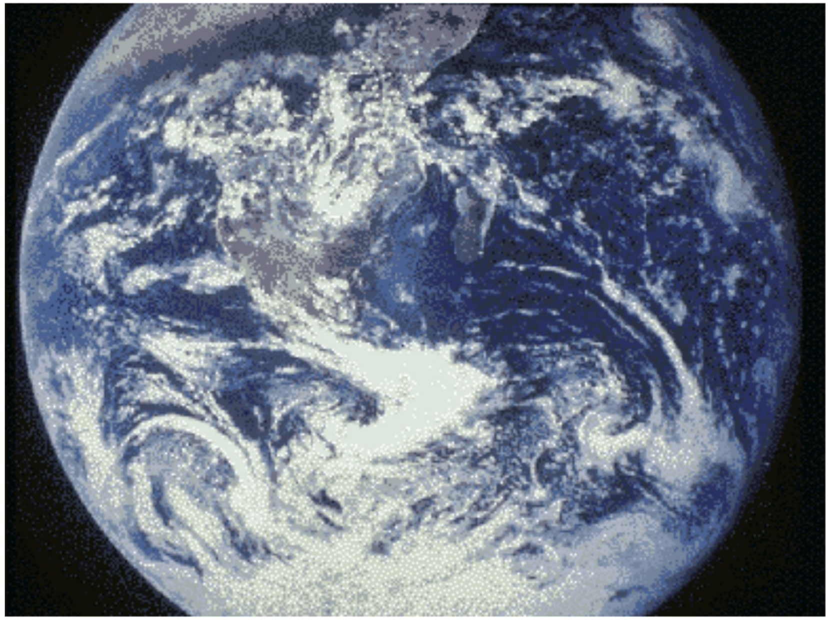
Source: Epidemiological data from the Atomic-bomb survivors with extrapolation to low dose:

For radiation protection we assume
ca. 50 cancer deaths
per 1 Million persons per 1 mSv.

= 5% / Sv

(linear dose-response relationship)

Natural radiation I



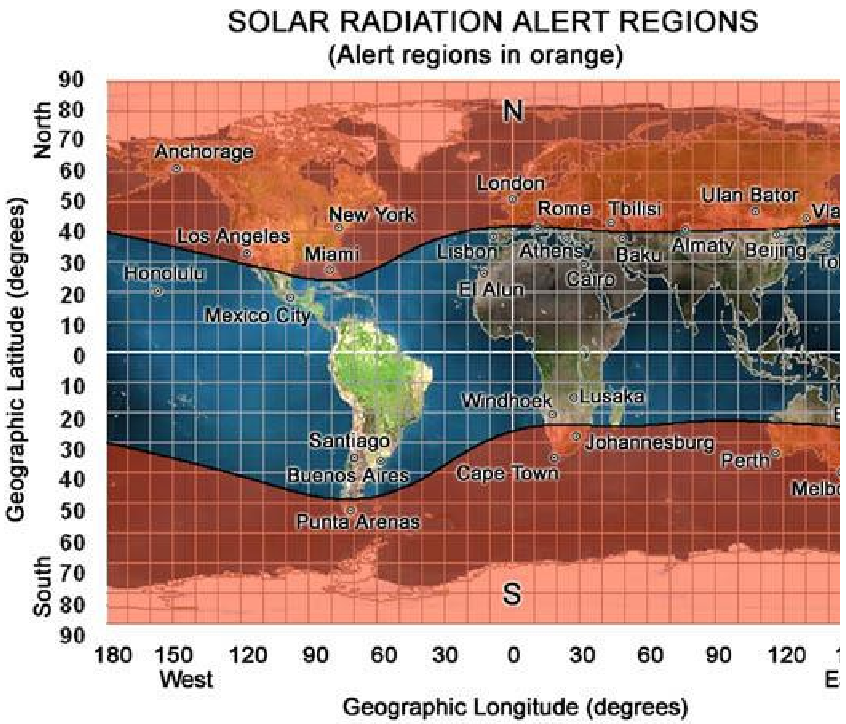
Biological effects of radiation:

- During it’s development life on earth was exposed to ionizing radiation.
- At the beginning of life radiation exposure was much larger than nowadays.
- Radiation contributed significantly to the evolution of life.

Natural radiation II

Cosmic radiation exposure:

- radiation from sun and outer space
- is increasing with increasing height
- mean exposure: 0.38 mSv/a



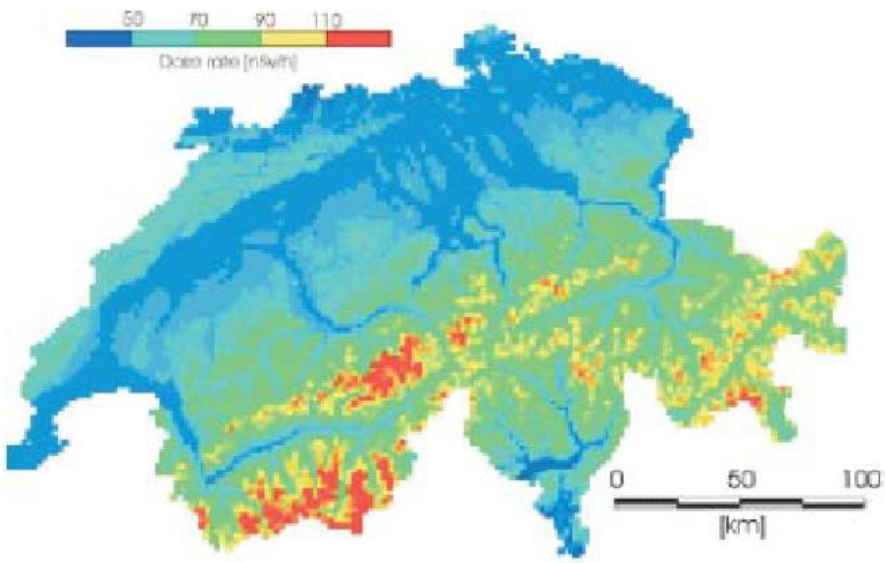
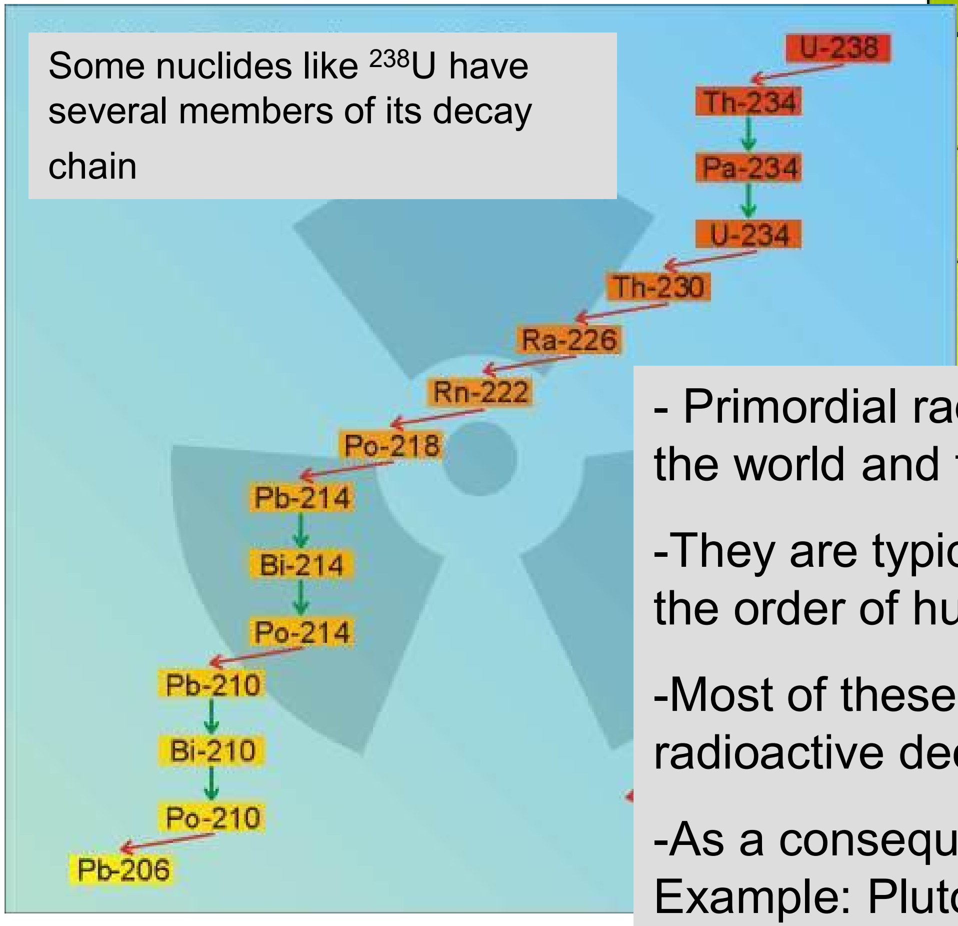


Fig. 2: Cosmic dose rate map (in nSv/h) of Switzerland. Min. value: 40 nSv/h; Max. value: 191 nSv/h; Average value: 64 nSv/h; Std. deviation 22 nSv/h.

Natural radiation III

Primordial radio-nuclides

Some nuclides like ^{238}U have several members of its decay chain



Zerfallsreihe	Beginn	Ende
Thorium-Reihe	$^{232}_{90}Th$	$^{208}_{82}Pb$
Uran-Actinum-Reihe	$^{235}_{92}U$	$^{207}_{82}Pb$
Uran-Radium-Reihe	$^{238}_{92}U$	$^{206}_{82}Pb$

- Primordial radio-nuclides are left over from when the world and the universe were created.

-They are typically long lived, with half-lives often on the order of hundreds of millions of years

-Most of these sources have been decreasing, due to radioactive decay since the formation of the Earth

-As a consequence some decay chains died out. Example: Plutonium-Neptunium-decay-chain

Natural radiation IV

Terrestrial radiation:

- from the earth crust
- major sources are natural radium, uranium and thorium
- Swiss alpes < 1.5 mSv/a
- Swiss Jura < 0.45 mSv/a

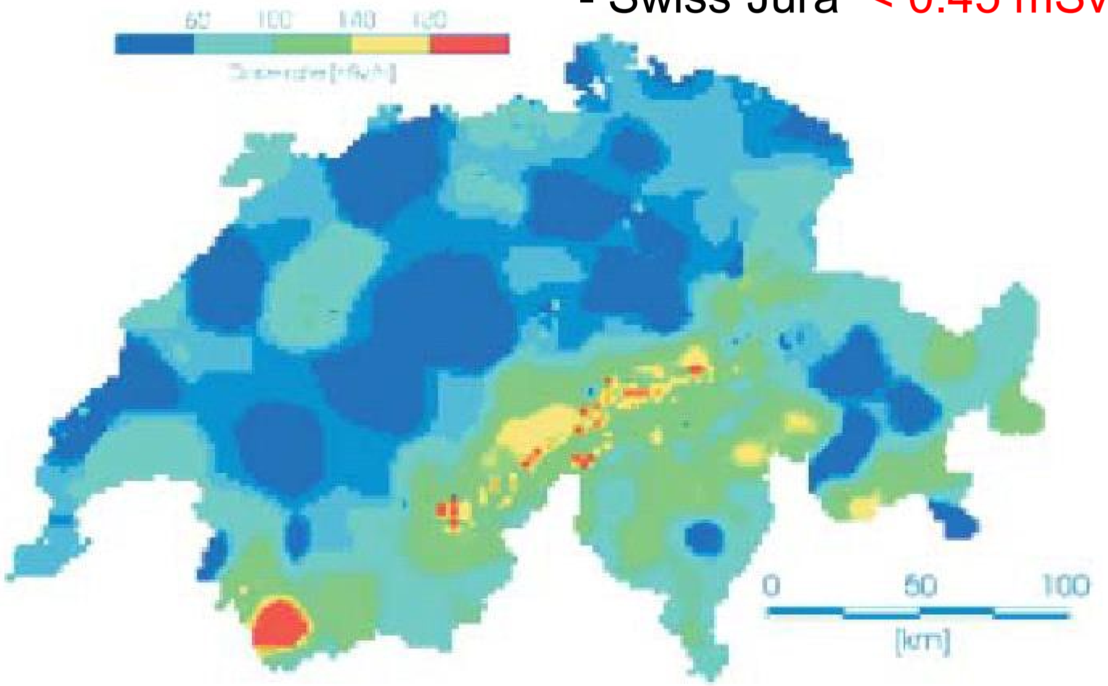


Fig. 3: Natural terrestrial dose rate map (in nSv/h) of Switzerland. Min. value: 6 nSv/h; Max. value: 368 nSv/h; Average value: 68 nSv/h; Std. deviation 35 nSv/h.

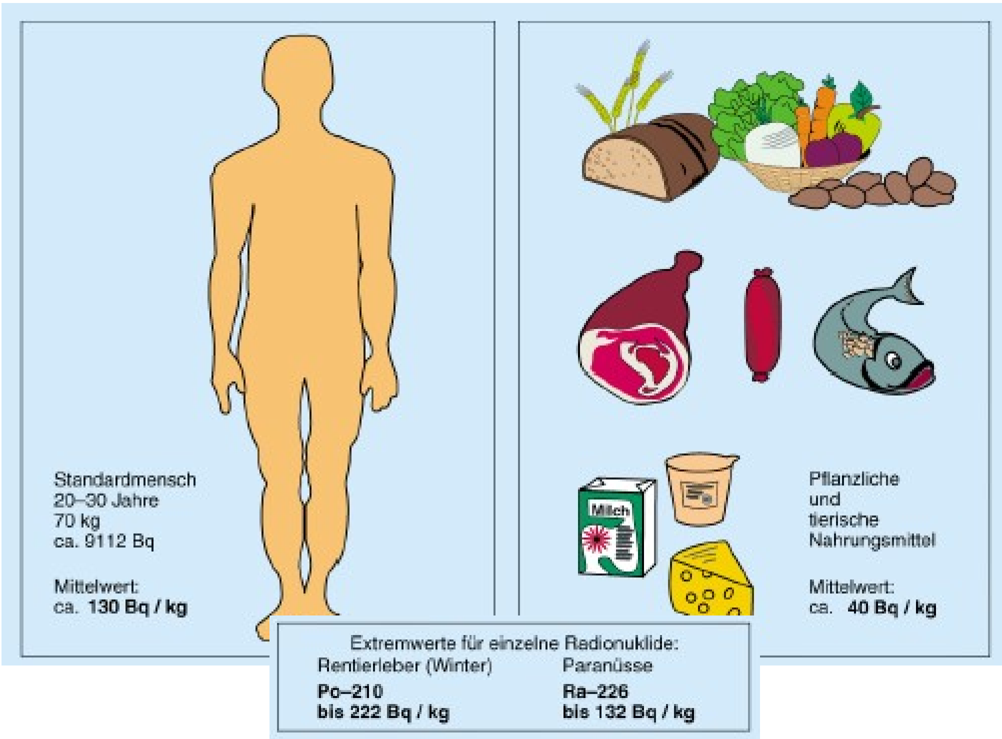
Natural radiation V

Radiation inside the human body:

- Some of the essential elements that make up the human body, mainly potassium and carbon, have radioactive isotopes that add significantly to our background radiation dose.
- Incorporated with food and water mainly in muscle.
- Water: nuclides from natural decay chains.
- 0.35 mSv/a

Radionuklid	Aktivität, Bq
K-40	4200
C-14	3800
Rb-87	650
Pb-210, Bi-210, Po-210	60
kurzlebige Radon-Zerfallsprodukte	45
H-3	25
Be-7	25
sonstige	10
Summe, gerundet	9100

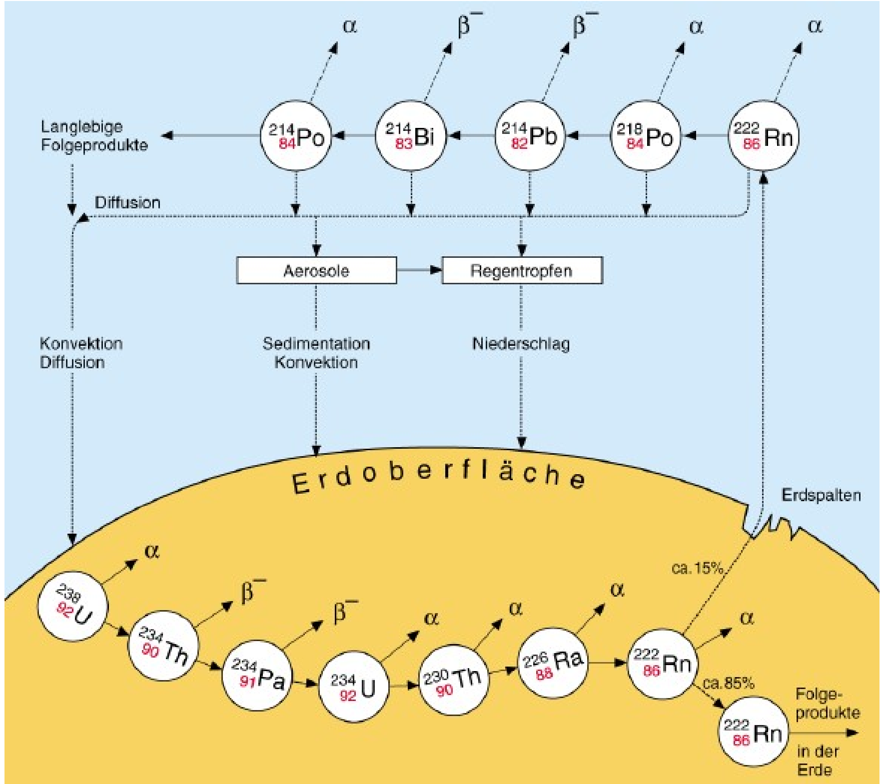
Tab. 7.9: Die wichtigsten natürlichen Radionuklide im Menschen

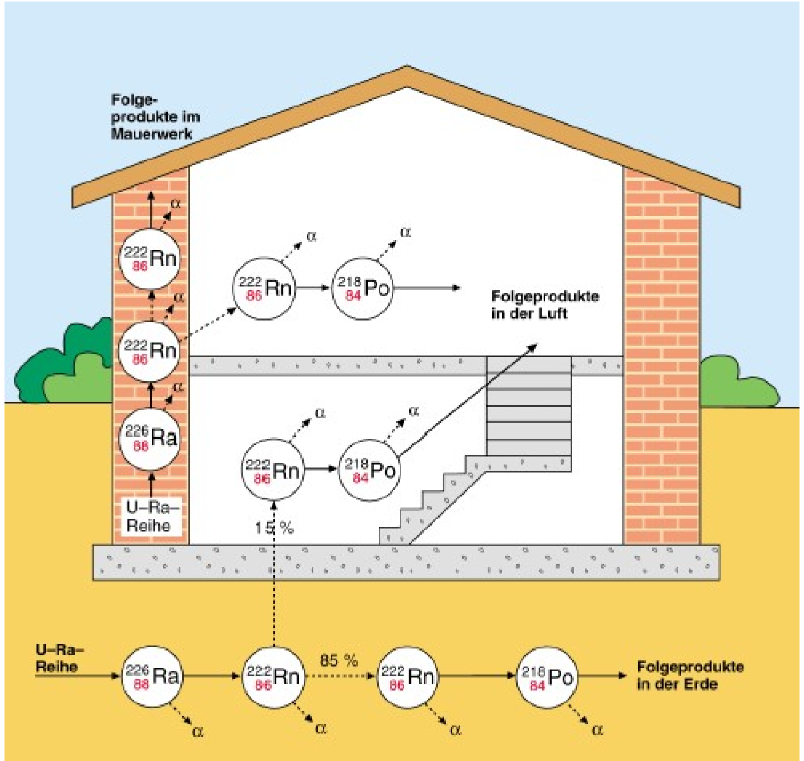


Natural radiation VI

Radon and decay products:

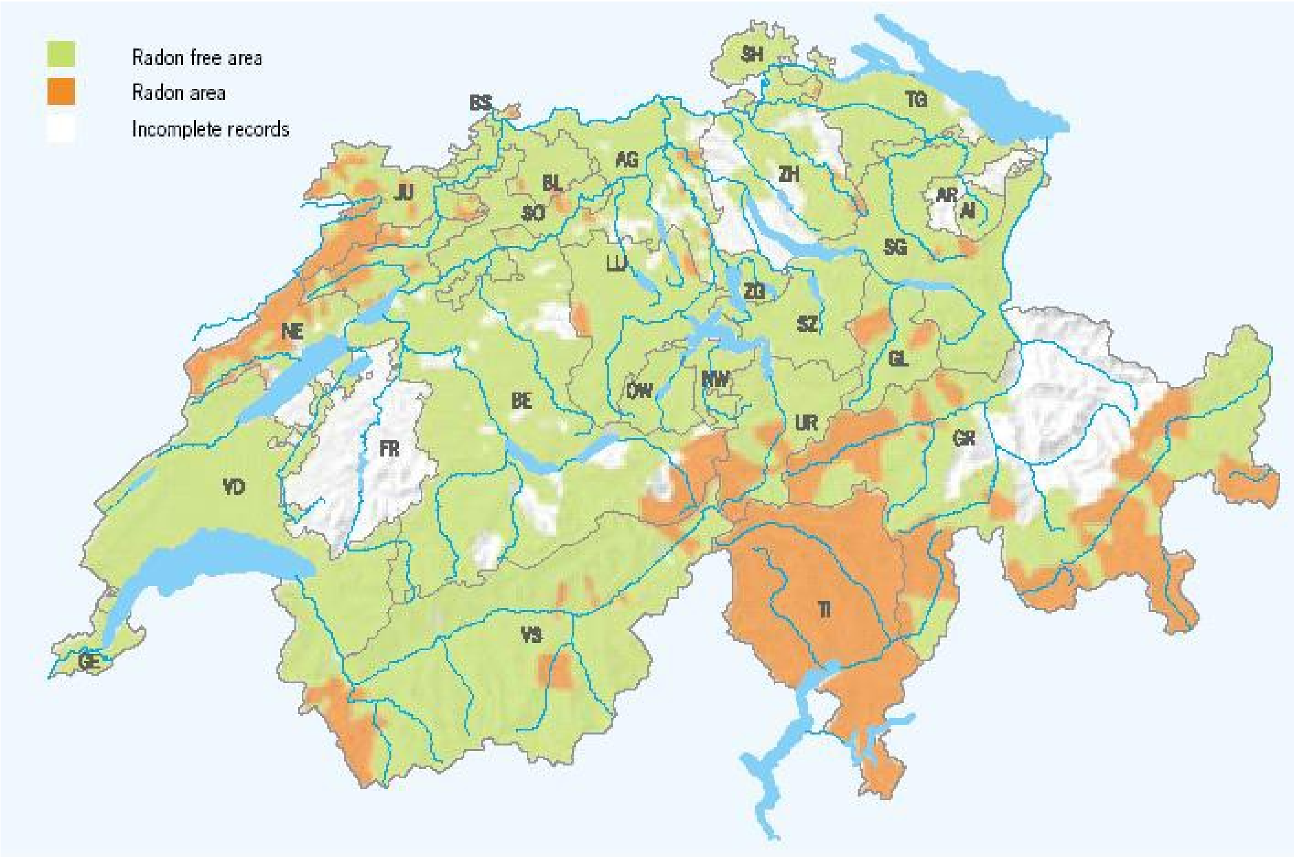
- Radon gas is a decay product of uranium, which is relatively common in the earth's crust.
- Radon has a short half-life (4 days) and can be inhaled and remain lodged in the lungs. It decays into other solid radioactive nuclides, causing continued exposure.





Natural radiation VII

Radon and decay products: 3.3 mSv/a (0.3 ... 100 mSv/a)



Natural radiation VIII

Total radiation exposure in Switzerland due to natural radiation exposure

4.5 mSv/a (1.0 ... 150 mSv/a)

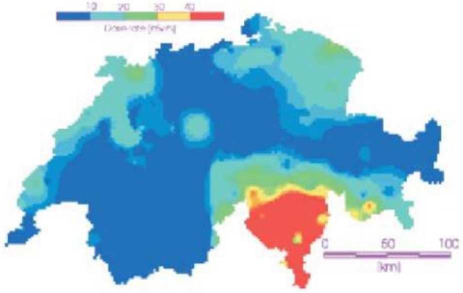


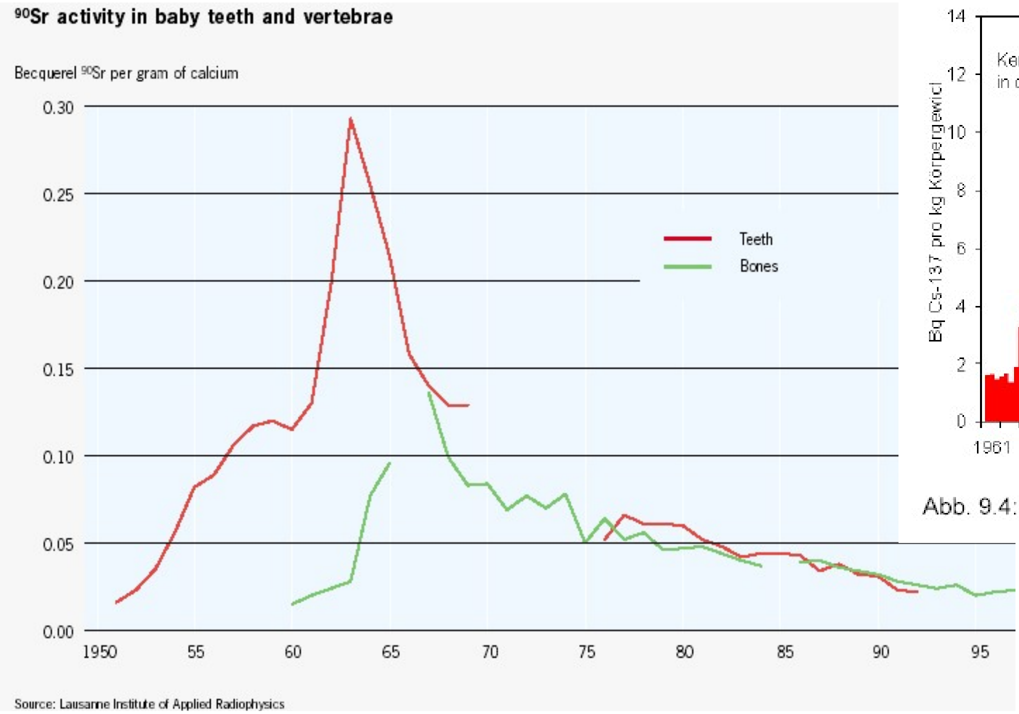
Fig. 4: Artificial dose rate map (in nSv/h) of Switzerland. Min. value: 1 nSv/h; Max. value: 91 nSv/h; Average value: 11 nSv/h; Std. deviation 14 nSv/h.

approximately 5% of 2’500 fatal cancers per year per 1 Million citizens originate from natural radiation (without Radon).

Artificial radiation sources I

Nuclear explosions and fallout:

- Frequent above-ground nuclear explosions between 1950-1965
- 50% local fallout, rendering the immediate surroundings highly radioactive
- 50% carried longer distances in the atmosphere; fallout due to rain.
- external and internal radiation exposure
- < 0.01 mSv/a



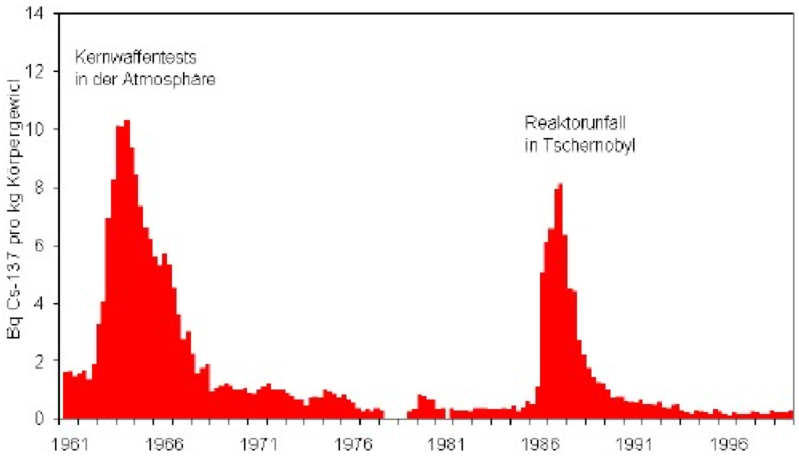


Abb. 9.4: Cs-137-Körperaktivität der Karlsruher Referenzgruppe

Artificial radiation sources II

Small sources

(Several materials contain radioactive nuclides):

- Illuminated displays, Glas, tiles, etc. < 0.01 mSv/a
- flying (cosmic radiation exposure): 0.03mSv/a
- Tobacco: 5 mSv/a (chain smoker); 0.03mSv/a (total)

Artificial radiation sources III

Nuclear reactors:

- Release of certain amounts of radioactive contamination

$<$ 0.01 mSv/a

Artificial radiation sources IV

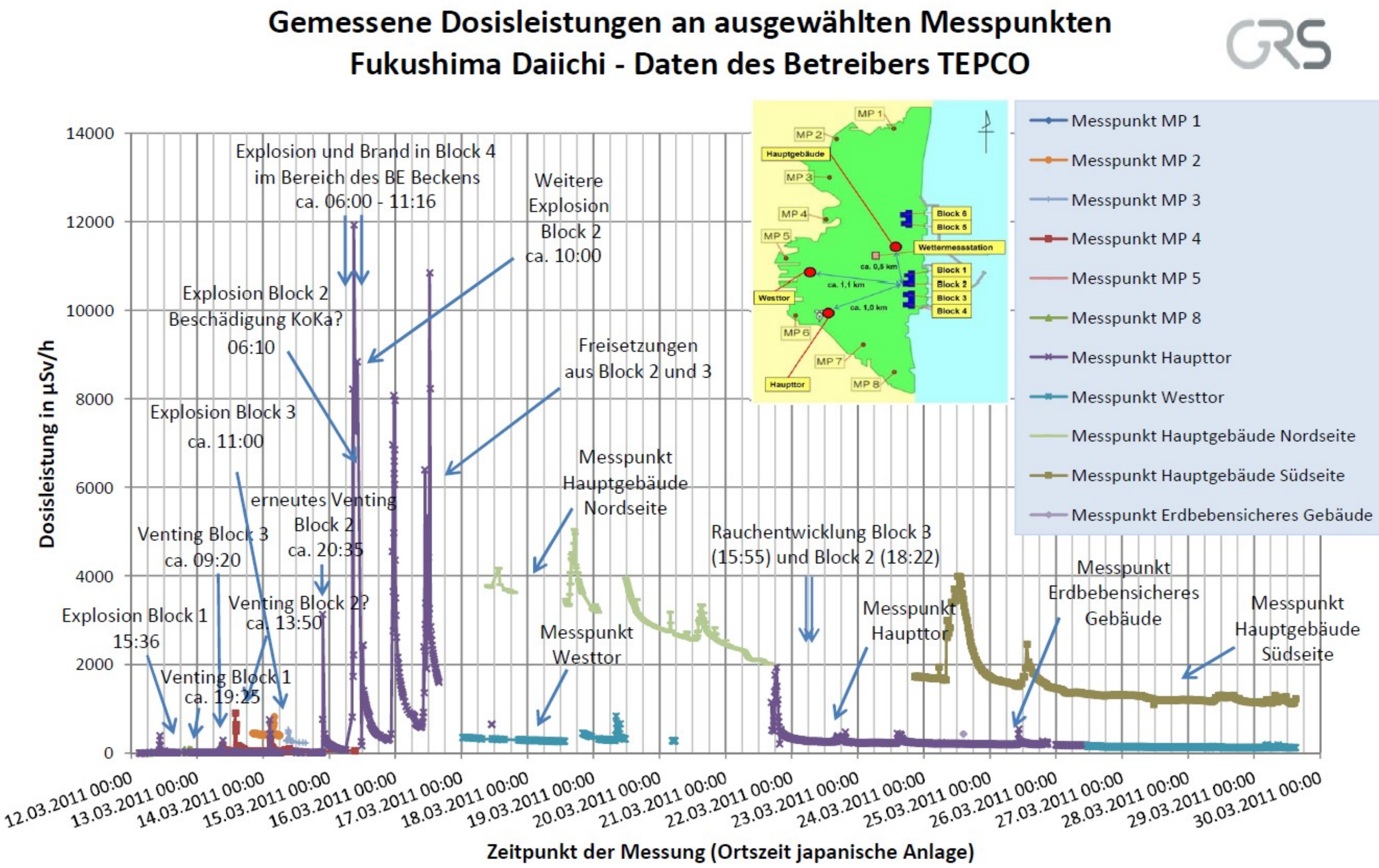
Tschernobyl accident (Exposure of Swiss citizens):

- Between 1986 and 2000 the mean effective dose was approximately 0.5 mSv (Maximum 5 mSv)
- Today mean effective dose: <0.01 mSv

Artificial radiation sources IVb

Fukushima accident in Japan

- After earth quake and Tsunami
- Breakdown of the cooling system after reactor-power-off and explosions
- Today mean effective dose: not measurable

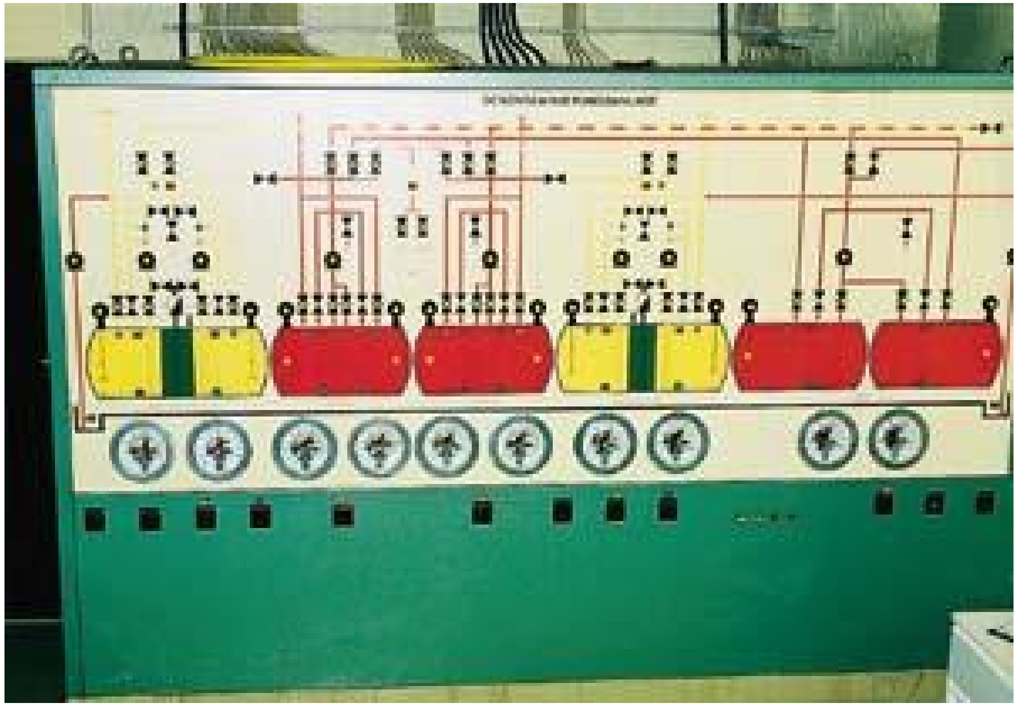


Artificial radiation sources V

Other sources:

- Industry, Research, Hospitals

< 0.03 mSv/a



Control unit of a liquid waste storage unit: monitoring of dose limits.
Liquid waste from hospitals may be radioactive contaminated and must be stored before releasing into canalisation.

Artificial radiation sources VI

Medicine:

- Radiation exposure in Radiology ~1.49 mSv/a (BAG 2022)
- Radiation exposure in Nuclear Medicine and Radiation-Oncology ~0.05 mSv/a

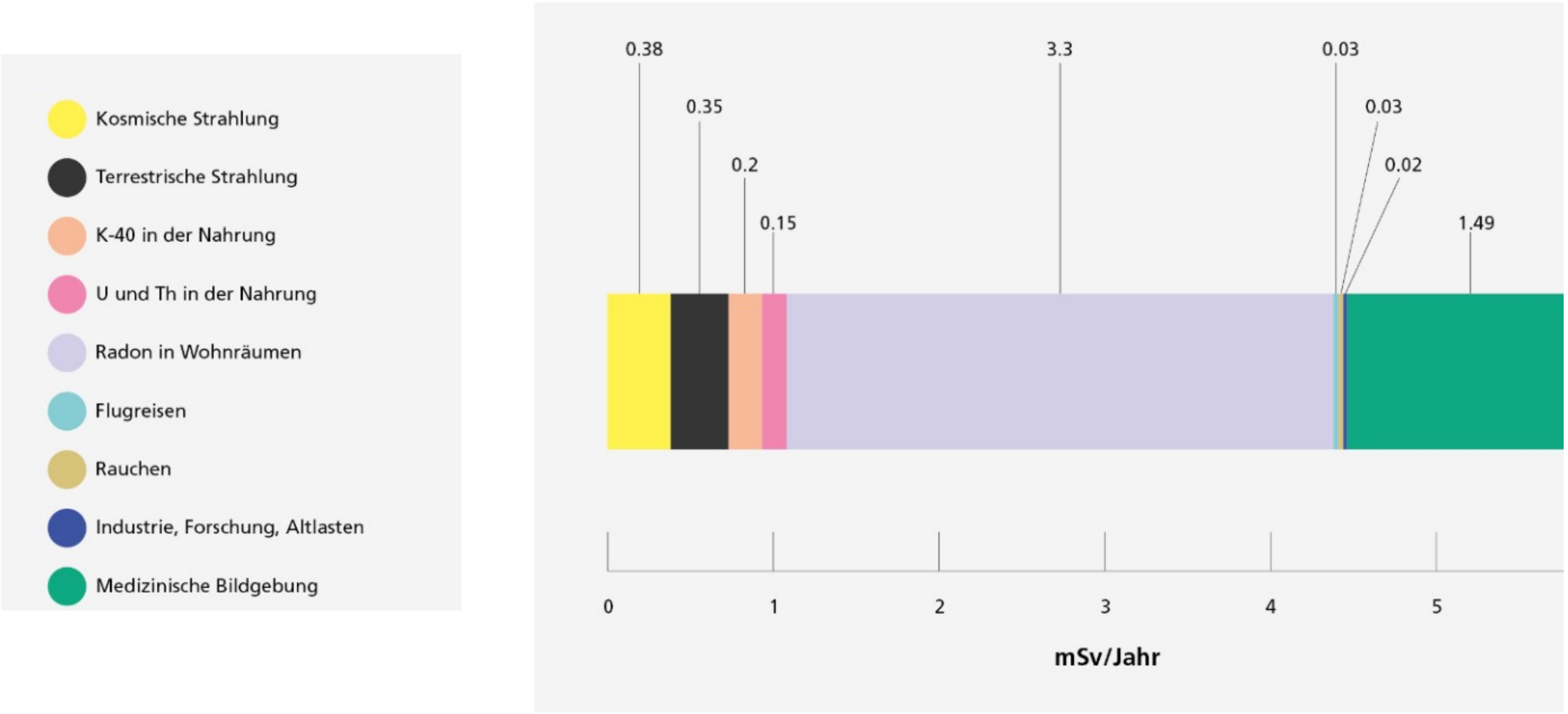
X-rays

Nuclear Medicine

Artificial radiation sources VII

Total artificial radiation in Switzerland:

1.6 mSv/a (there of 1.5 mSv/a from medicine)



Content

- Radiation protection when using diagnostic sources
- X-ray imaging in Radiation-Oncology
- MV imaging in Radiation Oncology
- IMRT
- Radiation Protection of personal

Radiation exposure of the patient

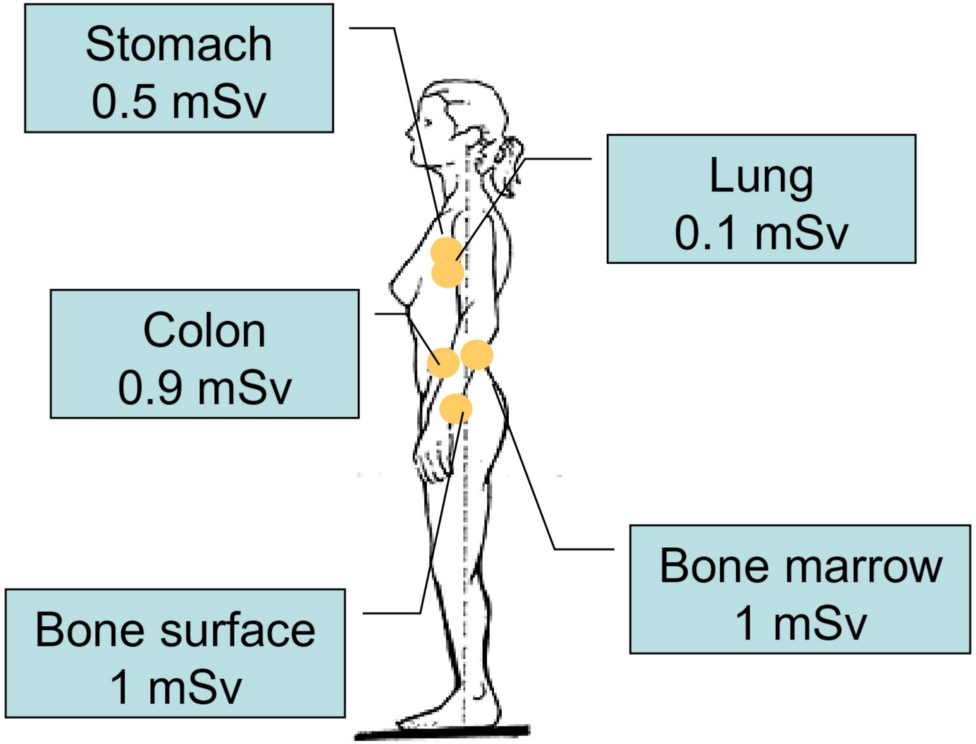
Radiation exposure during diagnostic x-rays

- Surface dose is largest dose in the patient
- Organ dose is usually in the order of mSv

If you compare with natural radiation keep in mind:
- Dose rate for diagnostic application can be 1'000'000 larger than with natural exposure.
- Effectiveness of radiation is increasing with increasing dose rate up to 1.5-2.0.

Example: Effective dose

Diagnostic image of the spine



Summary: Effective dose

Calculation of effective dose:

E = 1 x 0.5 mGy x 0.12 +
1 x 0.9 mGy x 0.12 +
1 x 1.0 mGy x 0.01 +
1 x 0.1 mGy x 0.12 +
1 x 1.0 mGy x 0.12

E = 0.31 mSv

To estimate effective dose we need to know:

1. Absorbed dose
2. Biological effectiveness of radiation
3. Equivalent dose
4. Weighting factors

Effective Dose

Effective Dose	Type of X-ray examination	Annual limit
> 200 mSv	Fluoroscopy, intervenitonal x-rays	
25 mSv	Bowel	
20 mSv		Occupational exposed
10 mSv	CT-Thorax CT-Abdomen	
5 mSv	Thoracic spine Abdomen	
2 mSv	CT-Scull Pelvis	Natural Radiation
1 mSv		General public
0.5 mSv	Scull	
0.2 mSv	Mammography	
0.1 mSv	Thorax Teeth	

Dose ranges: x-rays

Dose

Dose intensive examinations > 5 mSv
- Fluoroscopy/Simulation
- high-dose CT exposures (abdomen/whole body)

5 mSv

Medium dose range < 5 mSv and > 1 mSv

- Most CT-exposures

1 mSv

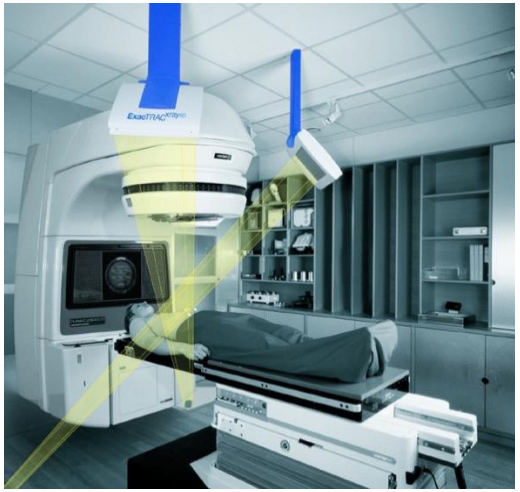
Low dose range < 1 mSv

- Single exposures of the Thorax
- Single exposures of extremities
- Single exposures of scull

IGRT

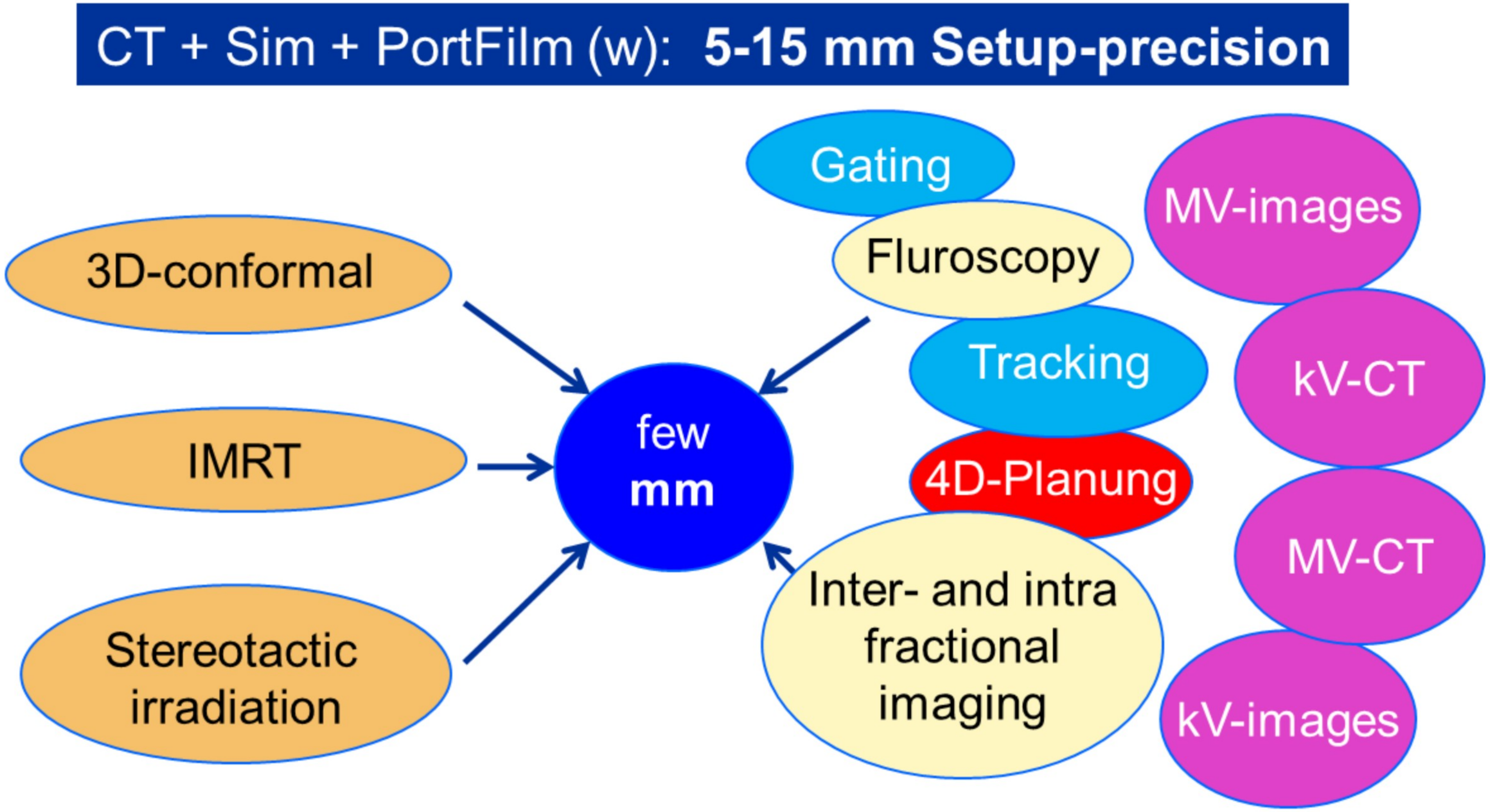

Fan Beam kV CT on
rails


TomoTherapy
Fan Beam
MV CT




CBCT
igrt
IMAGE GUIDED
RADIATION THERAPY

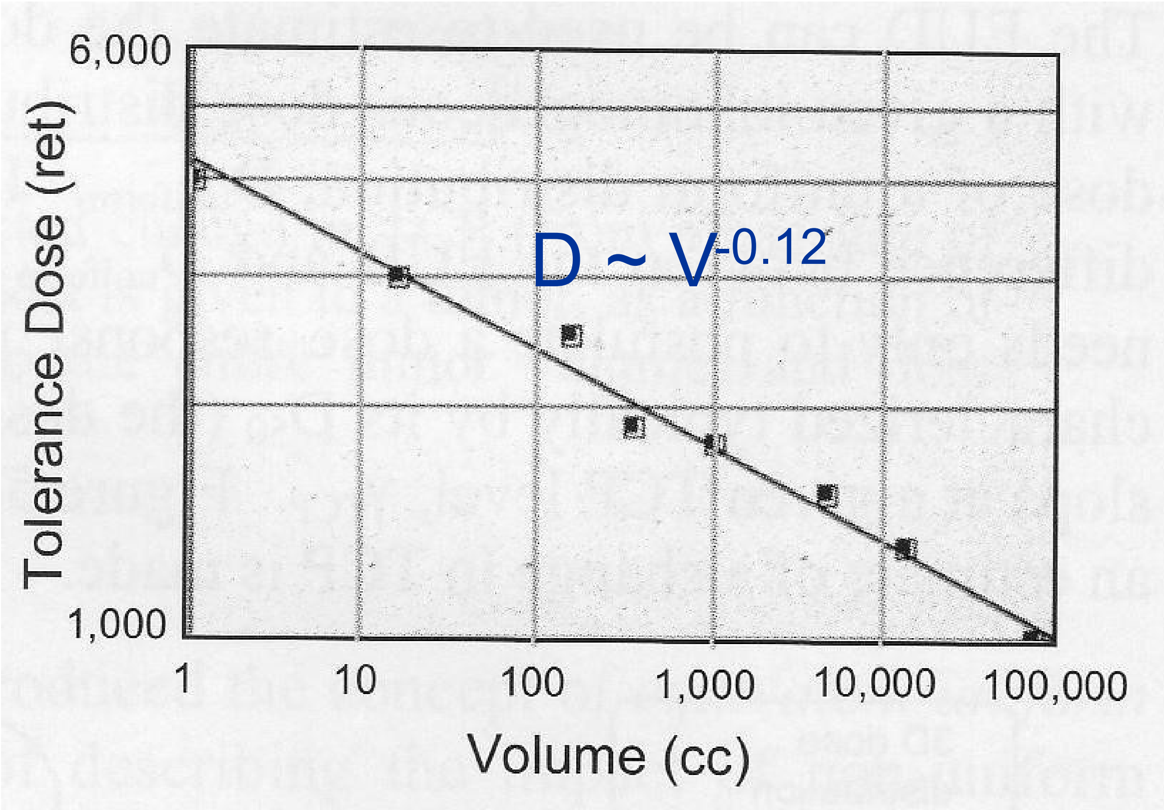
IGRT and Dose



- **How large is the additional dose ?**
- **Deterministic and/or stochastic effects ?**
- **Comparison with therapy dose ?**

The power of margin reduction I

Dose in clinical practice as a function of target volume



Assumption: Dose is limited by the morbidity of treatment

The power of margin reduction II

Example: Prostate treatment with volume of 200 cm^3 (r=3.6cm)

<u>Advantage of IGRT:</u>

Reduction of margin from 1 cm ⟶ 0.5 cm

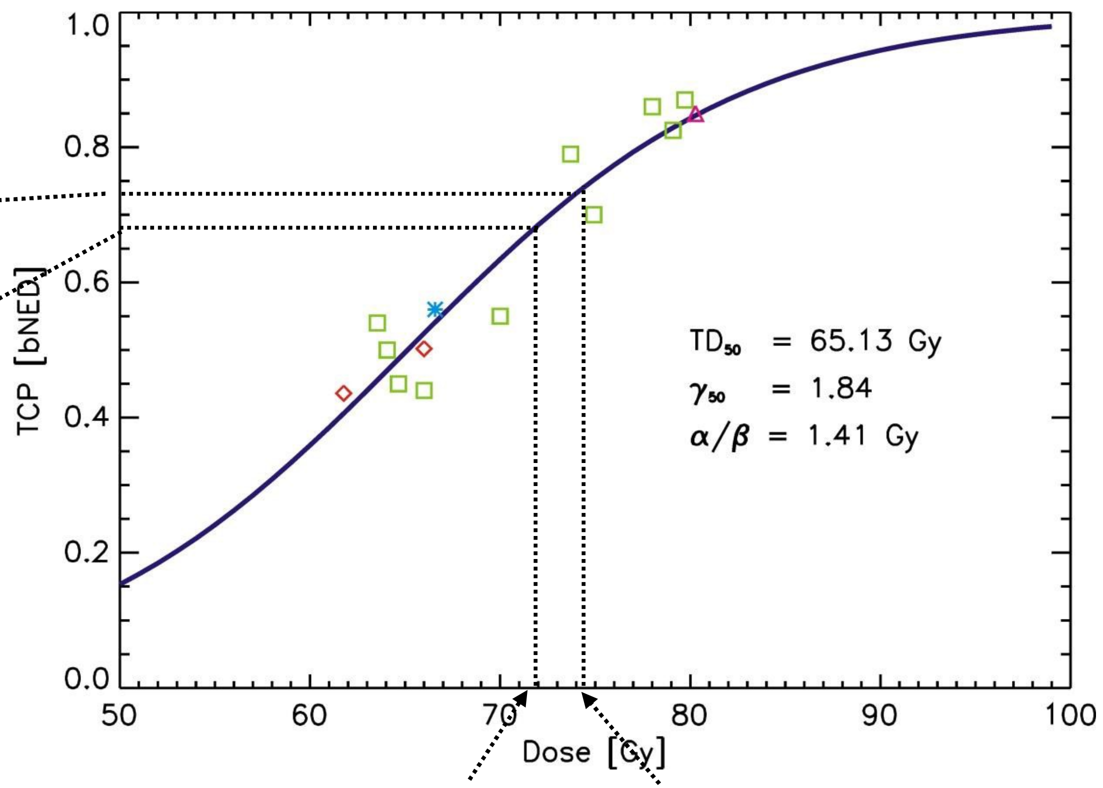
Volume reduction $V_{IGRT}/V_{noIGRT} = (3.1/3.6)^3 = 0.7$

TCP

71 %

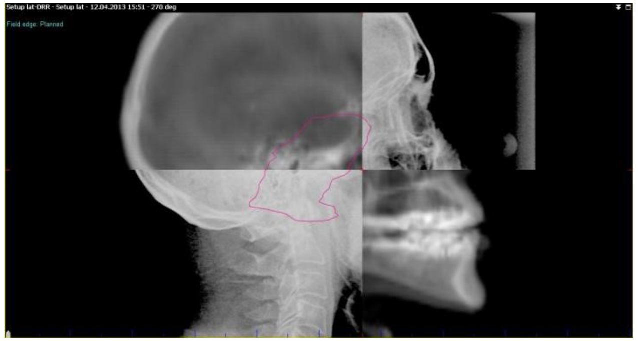
↑

65 %



72 Gy ⟶ 75 Gy

Consequences of the use of IGRT



Reduction of the treated volume

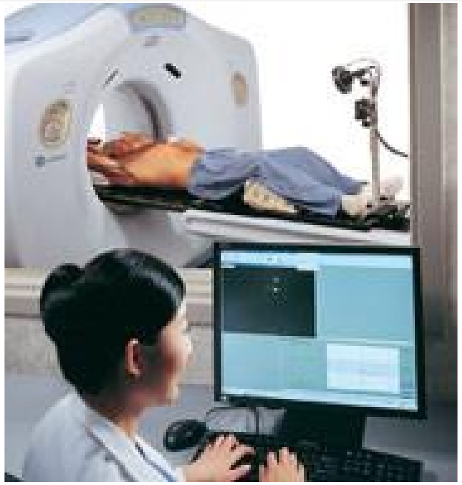
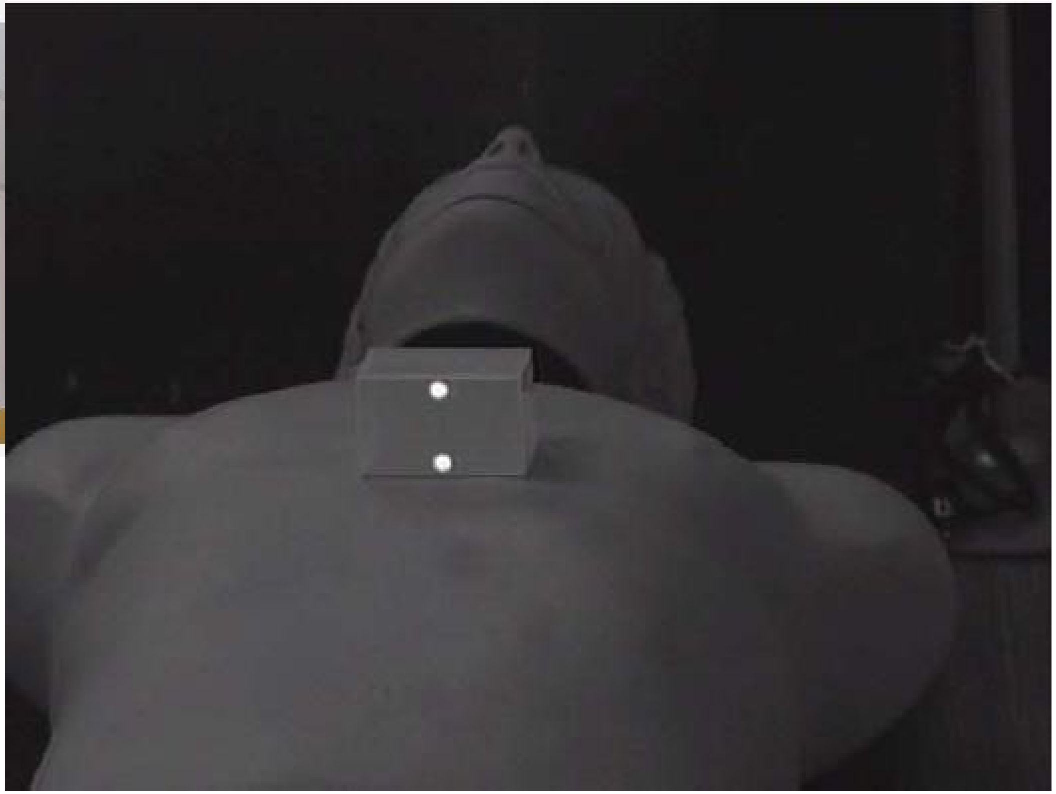
Additional dose from imaging

Less second cancers

More second cancers

4D-CT imaging I

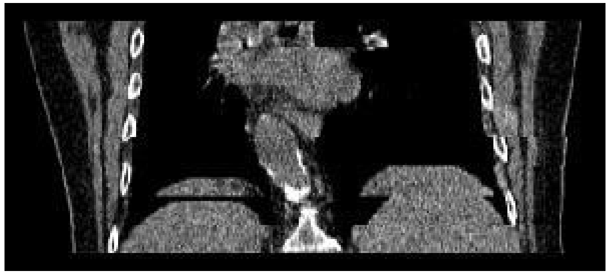
- Motion is registered during CT acquisition
- Patient is scanned multiple times at each couch position

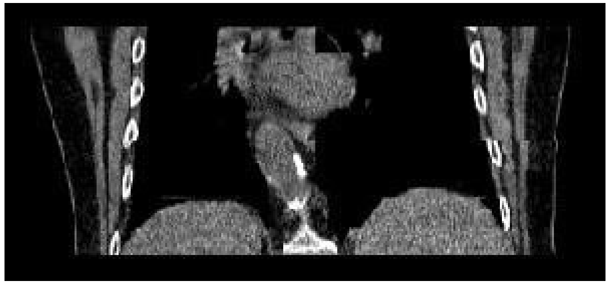
4D-CT imaging II

CT scans are sorted regarding the breathing cycle

3D imaging



4D imaging



Effective dose 3D			Effective dose 4D (maximum)
for head scan:	2 mSv	→	20 mSv
for abdomen scan:	5 mSv	→	50 mSv

IGRT kV/MV imaging

kV imaging

Dose for 1 exposure
~ 0.05 mSv

Treatment with 30 fractions and two Setup-fields:

Dose ~ 3 mSv

MV imaging

Dose for 1 exposure
~ 2…15 mSv

Treatment with 30 fractions and two Setup-fields:

Dose ~ 60…450 mSv

IGRT cone Beam CT

kV Cone Beam CT

Dose for 1 CT
~ 2 … 5 mSv

Treatment with 30 fractions and one Cone Beam CT:

Dose ~ 60 … 150 mSv

MV Cone beam CT

Dose for 1 exposure
~ 1 (Tomo) … 5 mSv

Treatment with 30 fractions and one Cone Beam CT:

Dose ~ 30 … 150 mSv

Effective dose from IGRT

IGRT treatment example 1

4D planning CT + 30 fractions of kV-guided radiotherapy + follow-up CT

D > 50 mSv

IGRT treatment example 2

4D planning CT + 30 fractions of CBCT guidance + follow-up CT

D > 200 mSv

Risk estimates for IGRT

Risk estimate with radiation protection schemes (ICRP): Life time cancer risk = 5%/Sv

IGRT treatment example 1

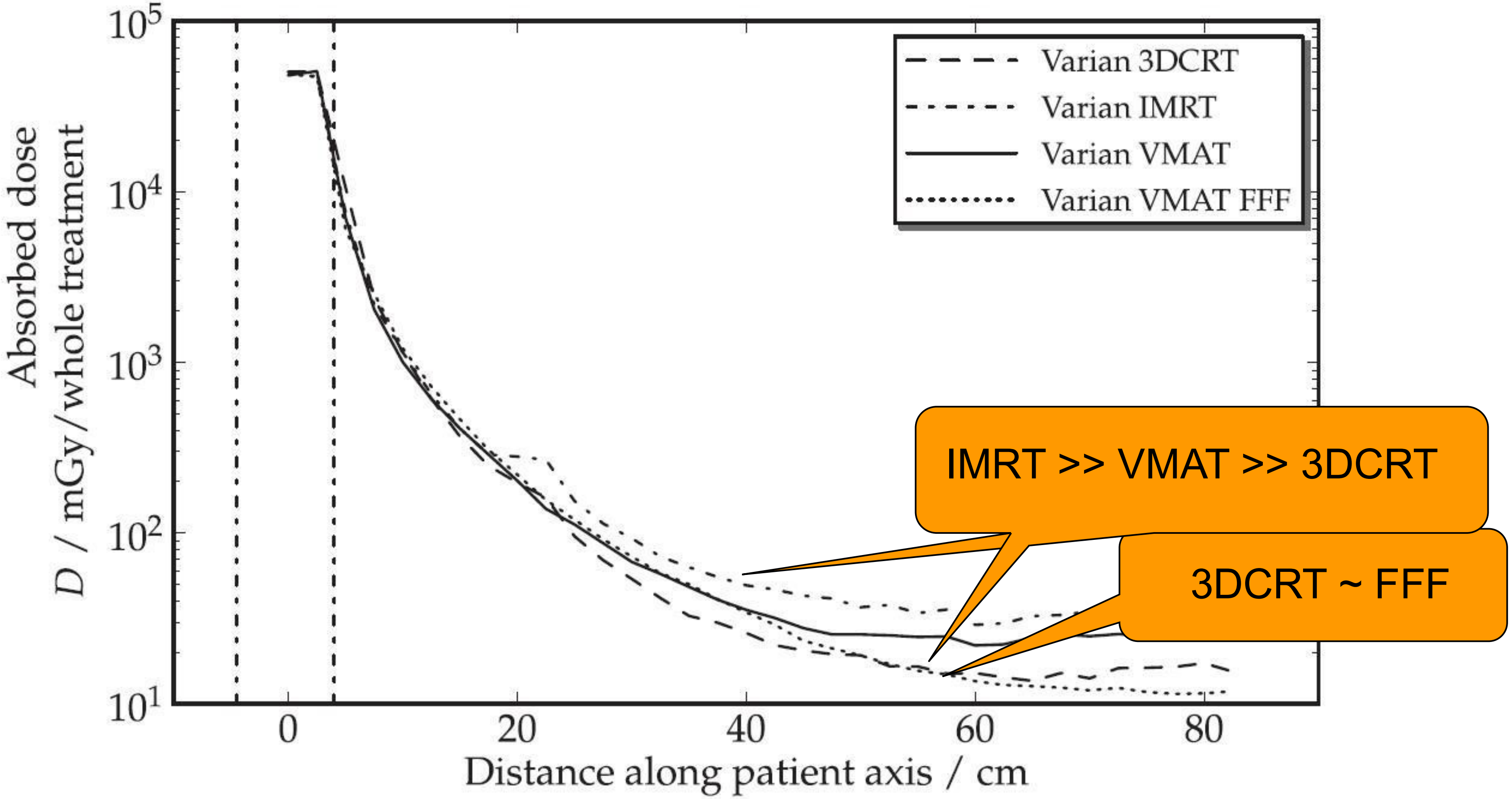
D = 50 mSv Risk = 0.2%

IGRT treatment example 2

D = 200 mSv Risk = 1%

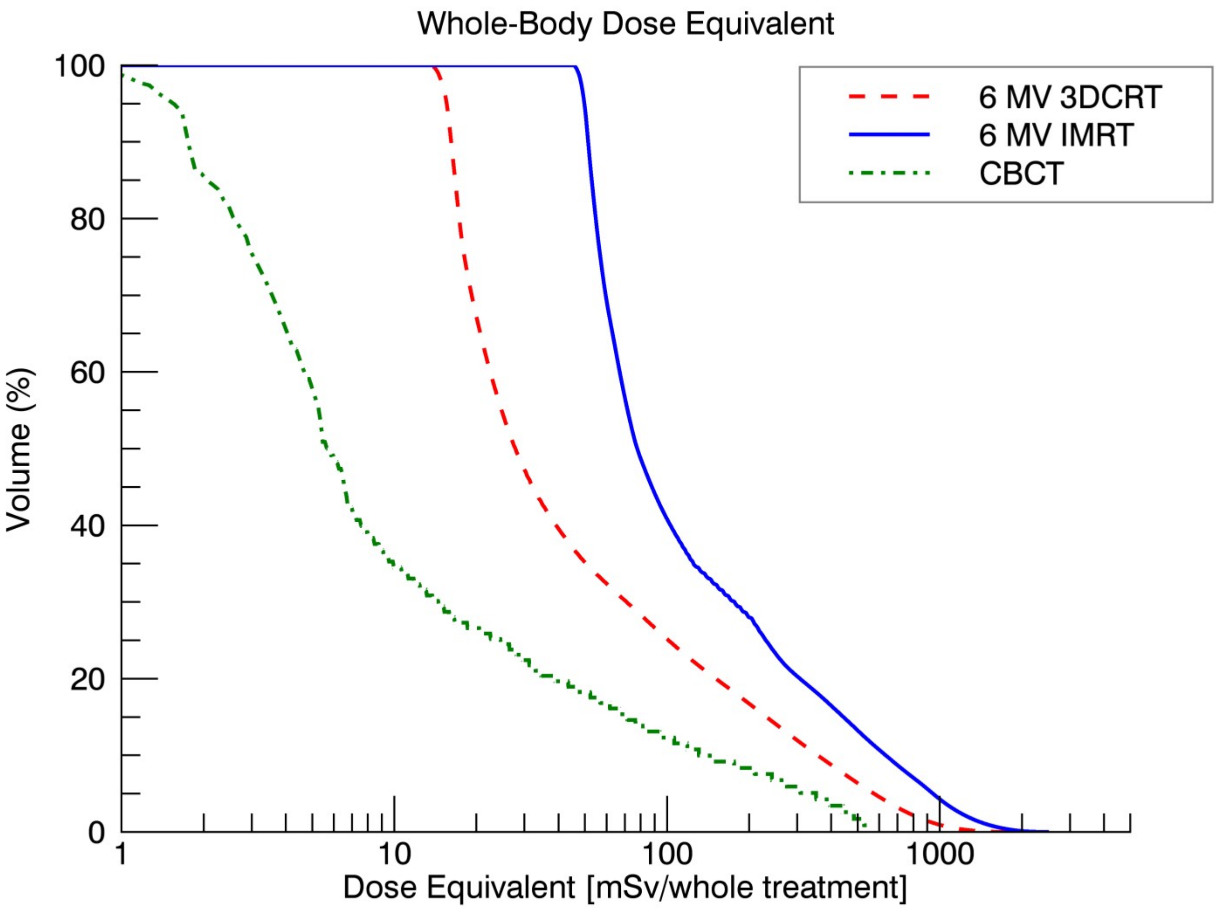
Comparison: 3DCRT vs. IMRT vs. VMAT

Young patient with Rabdomyosarcoma in the prostate



Comparison: 3DCRT vs. IMRT vs. CBCT

Young patient with Rabdomyosarcoma in the prostate



IGRT categories

Three categories for the quantification of imaging dose:

Category I:
The imaging dose is lower than a 2% variation of the therapy dose.

Category II:
The imaging dose is larger as defined by category I, but lower than the variation of therapy dose between different treatment techniques.

Category III:
The imaging dose is larger than the variation of therapy dose between different treatment techniques.

IGRT categories

Three categories for the quantification of imaging dose:

Category I: JUSTIFIED

The imaging dose is lower than a 2% variation of the therapy dose.

Category II: JUSTIFIED, if the advantage for the patient is comparable to the use of IMRT

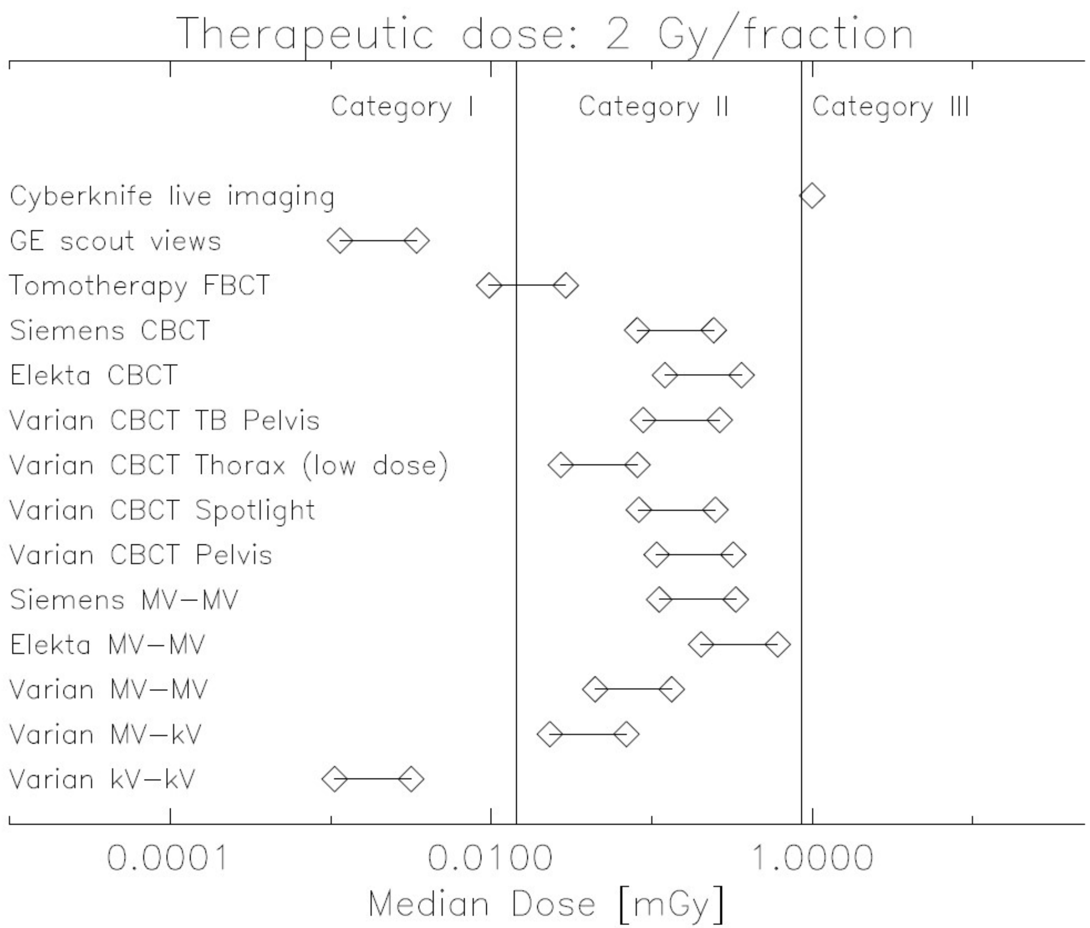
The imaging but lower than the variation of therapy dose between different treatment techniques.

Category III: needs additional JUSTIFICATION

The imaging dose is larger than the variation of therapy dose between different treatment techniques.

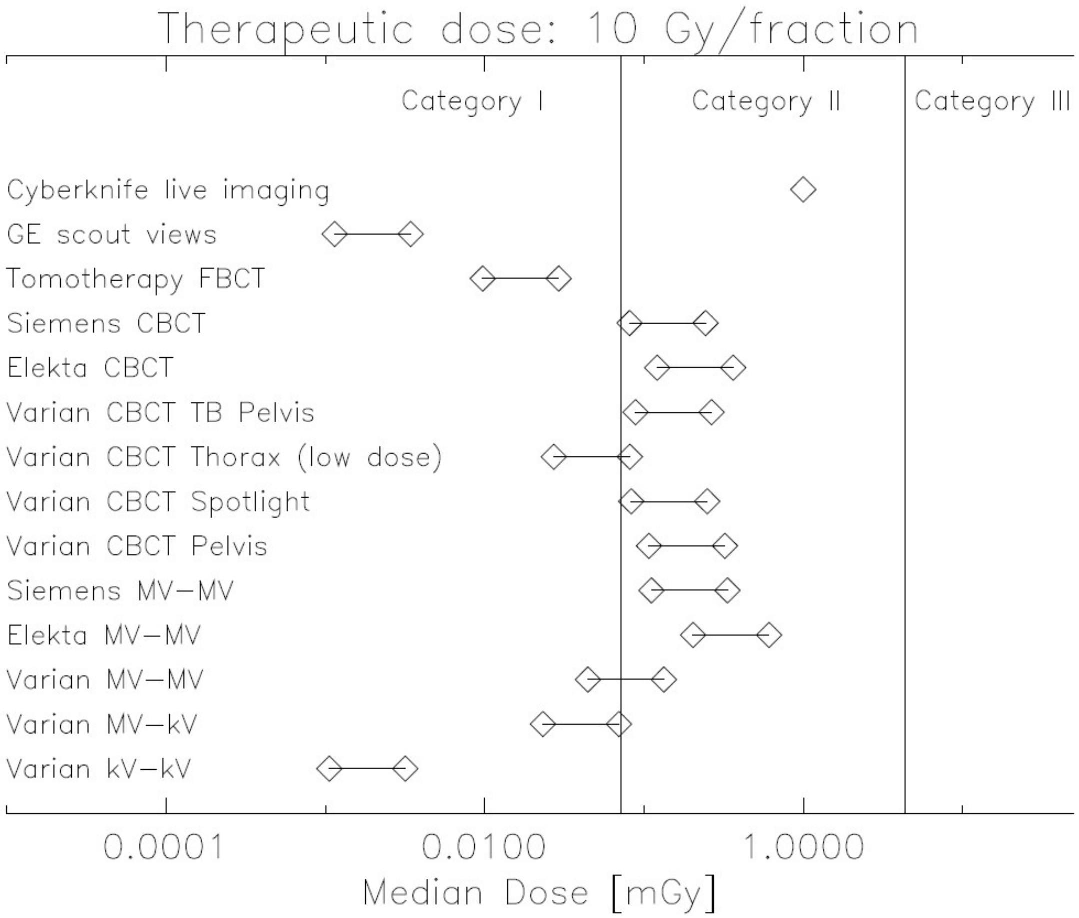
IGRT classification

Classification of various imaging modalities for a therapeutic dose of 2 Gy per fraction.



IGRT classification

Classification of various imaging modalities for a therapeutic dose of 10 Gy per fraction.



Content

- Governmental regulation
- Registration and license
- Responsibilities in a Radiation-Oncology clinic
- Radiation protection for the personal

Legislation

Swiss radiation protection legislation is based upon international recommendations of the **ICRP**

Organisation in Switzerland:

Parlament	Radiation protection legislation (StSG) from 1991
Bundesrat	Radiation protection regulation (StSV) from 2017
Departments	Implementation rules
BAG Bundesamt für Gesundheit	Regulatory authority for medicine, teaching and research
ENSI Eidgenössisches Nuklear-sicherheitsinspektorat	Regulatory authority for nuclear installations
SUVA Schweizerische Unfall-Versicherungsanstalt	Regulatory authority for industry

Principles

ALARA

As Low As Reasonably Achievable

- **Justification**
  - necessity and justification
  - benefit
  - benefit >> radiation risk
- **Optimization**
  - ALARA
- **Dose limits**
  - for general public and occupational exposed persons
  - no dose limits for patients

Principles

ALARA

As Low As Reasonably Achievable

In therapeutic medical exposure, optimization is achieved by keeping exposure of normal tissue ALARA consistent with delivering the required dose to the planning target volume (PTV).

- **Justification**
  - necessity and justification
  - benefit
  - benefit >> radiation risk
- **Optimization**
  - ALARA
- **Dose limits**
  - for general public and occupational exposed persons
  - no dose limits for patients

How to get a license

Setup and operation of a medical linear accelerator or a x-ray diagnostic device needs a license

Licensee (legal person)	Applies at BAG for a license - Radiation protection building plans - Radiation protection calculations
Contractor	Supports the lincensee

↓ Conditions fulfilled

BAG charters the license

↓

BAG inspection after installation

↓ Inspection ok

License with individual conditions (usually for 10 years valid)

Operation of a Linac

The operation of a linear accelerator requires:

- Existence of a medical expertise ("ärztliche Sachkunde")
- Assignment of a radiation protection officer ("Strahlenschutzsachverständige")
- Liability insurance
- The equipment must be up to date
- License of the BAG
- Implementation of a QA program
- Comply with radiation protection legislation

Responsibilities

Licensee (legal persons, usually hospital administration)	- responsibility that the hospital complies to radiation protection legislation - assign radiation protection officer - must guarantee safety in the hospital
Radiation protection officer (Medical Physicist)	- qualification as a Medical Physicist („Fachanerkennung“) - implement radiation protection rules in the clinic - responsibility for radiation protection
Medical expert (Radiation Oncologist)	- Qualification for Radiation-Oncology („Facharzt“) - medical responsibility for diagnostic and therapeutic application of ionising radiation to patients
Occupational exposed persons	- all persons which accumulate more than 1 mSv of dose - responsible for using their personal dosimeter

Personal dosimetry I

Determination of radiation dose (Dosimetry)
- Art.61 and Appendix 4-

The licensee must determine radiation exposure of all occupational exposed persons :

- on a monthly basis, by an accredited dosimetry lab.
- has to inform his employees about the measurements.
- has to pay the costs for the dosimetry.

Personal dosimetry

Determination of radiation dose (Dosimetry) (Art.42ff):

The licensee must determine radiation exposure of all occupational exposed persons :

- on a monthly basis, by an accredited dosimetry lab.
- has to inform his employees about the measurements.
- has to pay the costs for the dosimetry.

Data are stored in a “central dose registry” of BAG.

- no written documents anymore

Thank you for your attention!