BRACHYTHERAPY

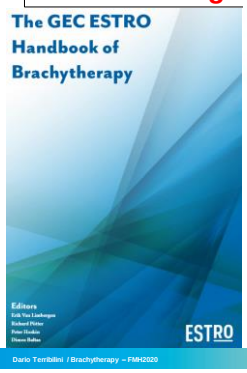
Dario Terribilini

INSELSPITAL
UNIVERSITÄTSSPITAL BERN
HÔPITAL UNIVERSITAIRE DE BERNE
BERN UNIVERSITY HOSPITAL

Dario Terribilini, Ph.D. SSRMP
Div. of Med. Radiation Physics
Inselspital - University of Berne
CH-3010 Berne
Switzerland
Phone: +41 31 632 1898
Fax: +41 31 632 2676
Email: dario.terribilini@insel.ch
www.ams.unibe.ch www.insel.ch

Division of Medical Radiation Physics

www.estro.org/



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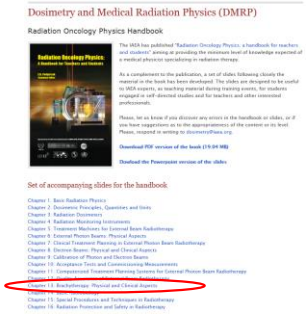

Dosimetry and Medical Radiation Physics (DMRP)

Radiation Oncology Physics Handbook

The IAEA has published "Radiation Oncology Physics: a handbook for teachers and students" aiming at providing the minimum level of knowledge expected of a medical physicist specializing in radiation therapy.

As a complement to the publication, a set of slides following closely the material in the book has been developed. The slides are designed to be useful to MDR experts, as teaching material during training courses, for students engaged in self-directed studies and for teachers and other interested professionals.

Please, let us know if you discover any errors in the handbook or slides, or if you have suggestions as to the appropriateness of the content or its level. Please, respond in writing to dosimetry@iaea.org.

Download PDF version of the book (19.04 MB)

Download the Powerpoint version of the slides

Set of accompanying slides for the handbook

Chapter 1: Basic Radiation Physics
Chapter 2: Dosimetric Principles, Quantities and Units
Chapter 3: Radiation Dosimetry
Chapter 4: Radiation Monitoring Instruments
Chapter 5: Treatment Machines for External Beam Radiotherapy
Chapter 6: External Photon Beams: Physical Aspects
Chapter 7: Clinical Treatment Planning in External Photon Beam Radiotherapy
Chapter 8: Electron Beams: Physical and Clinical Aspects
Chapter 9: Calibration of Photon and Electron Beams
Chapter 10: Acceptance Tests and Commissioning Measurements
Chapter 11: Computerized Treatment Planning Systems for External Photon Beam Radiotherapy
Chapter 12: Brachytherapy: Physical and Clinical Aspects
Chapter 13: Special Procedures and Techniques in Radiotherapy
Chapter 14: Radiation Protection and Safety in Radiotherapy

Chapter 13
Brachytherapy: Physical and Clinical Aspects

This set of 163 slides is based on Chapter 13 authored by N. Suntharalingam, E.B. Podgorsak, H. Tolli of the IAEA publication (ISBN 92-0-107304-6):

Radiation Oncology Physics:
A Handbook for Teachers and Students

Objective:

To familiarize students with basic physical and clinical principles of brachytherapy.

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Slide set prepared in 2006 (updated Aug2007) by E.B. Podgorsak (McGill University, Montreal)
Comments to S. Vatnitsky: dosimetry@iaea.org

13.1 INTRODUCTION

- Brachytherapy (also referred to as Curietherapy) is defined as a short-distance treatment of malignant disease with radiation emanating from small sealed (encapsulated) sources.
- The sources are placed directly into the treatment volume or near the treatment volume.

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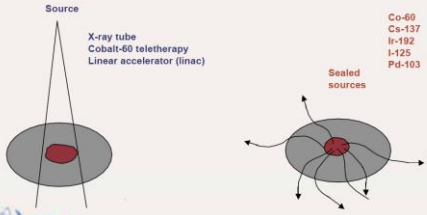
Radiation Oncology Physics: A Handbook for Teachers and Students - 13.1 Slide 1 (3/163)

13.1 INTRODUCTION

External beam radiotherapy
(external source of radiation)

Brachytherapy
(internal source of radiation)



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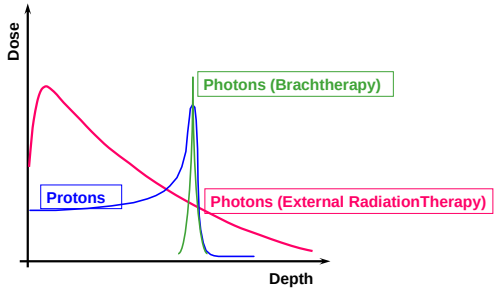
Introduction



13.1 INTRODUCTION

Brachytherapy compared to external beam therapy:

- Advantages of brachytherapy
  - Improved localized dose delivery to the target
  - Sharp dose fall-off outside the target volume
  - Better conformal therapy
- Disadvantages of brachytherapy
  - Only good for well localized tumors
  - Only good for small lesions
  - Very labor intensive

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13.1 INTRODUCTION

Brachytherapy sources:

- Photon sources
  Emit gamma rays through gamma decay and possibly characteristic x rays through electron capture and internal conversion
  (examples: Co-60, Cs-137, Ir-192, I-125, Pd-103)
- Beta sources
  Emit electrons following beta source decay
  (example: Sr-90/Y-90)
- Neutron sources
  Emit neutrons following spontaneous nuclear fission
  (example: Cf-252)
- Miniature X-Ray sources (50 kV)

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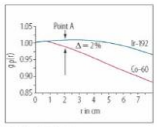
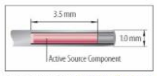
Radiation Oncology Physics: A Handbook for Teachers and Students - 13.1 Slide 5 (7/163)

13.2 PHOTON SOURCE CHARACTERISTICS
13.2.1 Practical considerations

- Dosimetric characteristics of brachytherapy sources:
  - Photon energy
  - Half-life
  - Half-value layer in shielding materials
  - Specific activity
  - Source strength
  - Inverse-square dose fall-off



Radial Dose Rate Function



Miniaturised Co-60 Source for HDR afterloading

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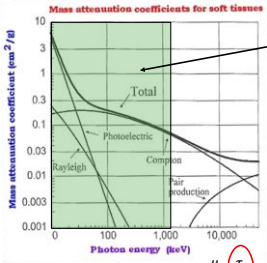
Photon Source Characteristics – Physics



Brachytherapy

Mass attenuation coefficient: $\frac{\mu}{\rho} = \frac{\tau}{\rho} + \frac{\sigma}{\rho} + \cancel{\frac{\kappa}{\rho}} + \frac{\mu_{el}}{\rho}$

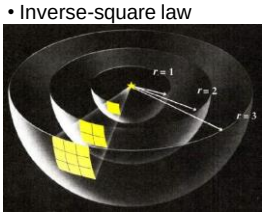
Photoelectric effect ($\tau_{photo} \sim Z^{-4} E_\gamma^{-3}$) **Pair production**

Compton effect **Elastic scattering**

Photon Source Characteristics – Physics

- Photon Energy of the brachytherapy source influences:
  - Penetration into tissue
  - Radiation protection requirements

- Inverse-square law



Photon Source Characteristics – Radioactive decay

$$N(t) = N_o e^{-\lambda t}$$

where:

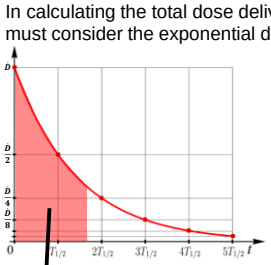
- N_o is the initial number of radioactive atoms
- N is the number of radioactive atoms at time t
- λ is the decay constant
  - $\lambda = \frac{ln2}{t_{½}}$, and $t_{½}$ is the half-life of the radionuclide

Further, the mean-life T_{avg} of an isotope is defined as the time taken to decay to 1/e of the original number of atoms:

$$\frac{N(t)}{N_o} = e^{-1} \Rightarrow \lambda t = 1 \Rightarrow T_{avg} = \frac{T_{½}}{\ln 2} = 1.44 * T_{½}$$

Cumulative Dose

In calculating the total dose delivered during the implant one must consider the exponential decay of the source strength.



$$D_{cum}(t) = \int_0^t \dot{D}(t)\,dt = \dot{D}_o \int_0^t e^{-\lambda t} dt = \frac{\dot{D}_o}{\lambda}\{1 - e^{-\lambda t}\} = \frac{T_{1/2}\dot{D}_o}{ln(2)}\left\{1 - e^{-\frac{t*ln(2)}{T_{1/2}}}\right\}$$

Cumulative Dose

$$D_{cum} = \frac{T_{1/2}\dot{D}_o}{ln(2)}\left\{1 - e^{-\frac{t*ln(2)}{T_{1/2}}}\right\}$$

Permanent implants: $t \gg T_{1/2}$

$$\Rightarrow D_{cum} = \frac{T_{1/2}\dot{D}_o}{ln(2)}\left\{1 - \cancel{e^{-\frac{t*ln(2)}{T_{1/2}}}}^{\,0}\right\}$$

$$\boldsymbol{D_{cum} = \frac{T_{1/2}\dot{D}_o}{ln(2)}}$$

Temporary implants: $t \ll T_{1/2}$

$$\Rightarrow D_{cum} = \frac{T_{1/2}\dot{D}_o}{ln(2)}\left\{1 - \cancel{e^{-\frac{t*ln(2)}{T_{1/2}}}}^{\,1-\frac{t*ln(2)}{T_{1/2}}}\right\}$$

$$\boldsymbol{D_{cum} = \dot{D}_o t}$$

Photon Sources

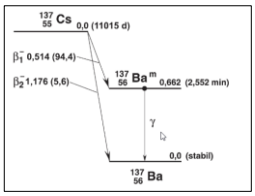
Radionuclides Photons

Radionuklid	Energiebereich E (keV)	Mittlere Energie < E > (keV)	HVL_{Pb} (mm)	Halbwertszeit $T_{1/2}$	Anwendungs-art	$A_{spezifische}$ (GBq/g)
^{226}Ra	47-2450	830	8.0	1620y	temporär	37
^{241}Am	------	60	0.125	432y	temporär	125.8
^{137}Cs	------	662	5.5	30y	temporär	295.8×10^1
^{60}Co	1170, 1330	1250	11	5.26y	temporär	40.7×10^3
^{192}Ir	136-612	380	2.5	73.9d	temporär	340.4×10^3
^{124}I	27-35	28	0.025	59.6d	permanent	62.9×10^4
^{169}Yb	10-308	93	0.2	32d	permanent	88.8×10^4
^{103}Pd	20-23	21	0.008	17d	permanent	277.5×10^4
^{198}Au	------	412	2.5	2.7d	permanent	88.8×10^5

Cesium 137

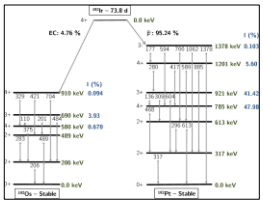
Cesium 137, a fission byproduct, is a popular radium substitute because of its 30-year half-life.

Its single γ-ray (0.66 MeV) is less penetrating (HVL_{Pb} = 0.65 cm) than the γ-rays from radium (HVL_{Pb} = 1.4 cm) or ^{60}Co (HVL_{Pb} = 1.1 cm).
Because ^{137}Cs decays to solid barium 137, ^{137}Cs sources have virtually replaced ^{226}Ra intracavitary tubes in LDR gynecologic applications.



Iridium 192

^{192}Ir is produced in the nuclear reactor in the reaction $^{191}Ir(n,\gamma)^{192}Ir$. ^{191}Ir composes 37.3% of natural iridium, ^{193}Ir making 62.7%.



Complex decay pattern leading to a photon spectrum with mean energy of ca. 380 keV

High specific activity➔small sources

Half life: 73.8 days

Palladium 103

^{103}Pd can be produced:

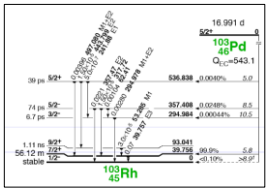
- By neutron activation of ^{102}Pd: ^{102}Pd(n,γ)^{103}Pd. (^{102}Pd occurs only at 0.9% level)
- By nuclear reaction with a proton beam on rhodium 103: ^{103}Rh(p,n)^{103}Pd. (natural abundance of ^{103}Rh: 100%).

In practice, this isotope can be produced with a very high specific activity, more than 2500 GBq/mg.

^{103}Pd decays by electron capture to excited states of Rh-103 followed by characteristic x-ray emission 20-23 keV photons (average 21 keV)

Half-life: 17 days

Widely used for permanent implants



Iodine 125

^{125}I is produced mainly in a neutron capture process (in reactors), through xenon 124 (^{124}Xe) gas target: ^{124}Xe(n, γ)^{125}Xe.

^{125}Xe decays into ^{125}I by electron-capture (EC) transition: ^{125}Xe → ^{125}I + ν + E_b.

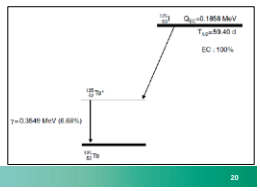
^{125}I decays by EC into an excited state ^{125}Te*, producing the maximum photon energy of 35.5 keV by gamma decay (6.7% of the time).

In addition, the transition leads to characteristic x-rays of energy between 27.2 to 31.7 keV (K-shells) as a result of internal conversion (93.3%).

The specific activity of ^{125}I is more than 600 GBq/mg

Half life: 59.4 days

Iodine seeds are widely used for permanent implants (prostate seed implants) and also eye plaques.



Photon Source Characteristics

High Dose Rate Brachytherapy Sources

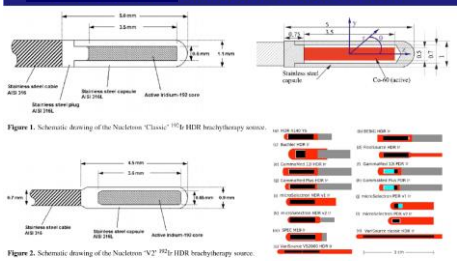
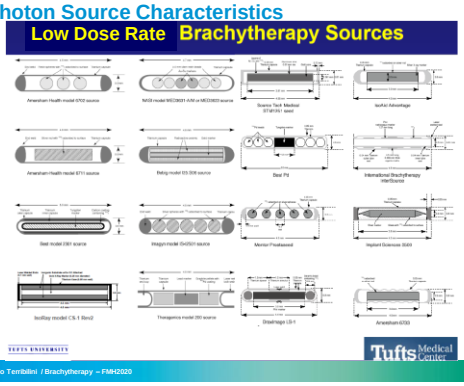


Figure 1. Schematic drawing of the Nucletron 'Classic' ^{192}Ir HDR brachytherapy source.

Figure 2. Schematic drawing of the Nucletron 'V2' ^{192}Ir HDR brachytherapy source.

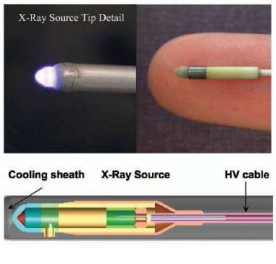
Photon Source Characteristics

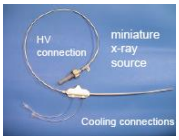


Photon Source Characteristics

Electronic X-Ray Source

- 50 kV, 0.3 mA, 15 W
- Water cooled
- Can be used as HDR source





Rivard et al, Med Phys. 33(11), 2006

Photon Source Characteristics – Source Specification

Activity

Historic units:

- For Radium: [mg Ra] ➔ «Dose» specification in [milligram-hours]
- For other nuclides: [mg Ra equivalent]
- 1 [Ci] = 1 [mg Ra] = 3.7 * 10^{10} [disintegration / sec]

SI Unit

- 1 [Bq] = 1 [disintegration / sec] ➔ 1[Ci] = 3.7 * 10^{10} [Bq]

Photon Source Characteristics – Source Specification

The amount of radiation emitted depends on the source geometry (filtration and self absorption)

Specification of source strength as “activity”

- Difficult to measure accurately and reproducibly both by the vendor and the user
- Variability in the factor to convert activity to dose in the patient

13.2 PHOTON SOURCE CHARACTERISTICS
13.2.4 Source specification

- Specification of gamma ray sources:
  - (1) Reference air kerma rate in air $(\dot{K}_{air}(d_{ref}))_{air}$
  - (2) Air kerma strength S_K
  - ~~(3) Exposure rate in air $\dot{X}_p$~~
  - (4) Air kerma rate in air $(\dot{K}_{air}(d))_{air}$

KERMA is an acronym for Kinetic Energy Released per unit MAss.
In this context, the kerma is defined as the mean energy transferred from the indirectly ionizing radiation to charged particles (electrons).
The unit of kerma is Joule per kilogram = Gray.

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13.2 PHOTON SOURCE CHARACTERISTICS
13.2.4 Source specification

- Specification of gamma ray sources:
  - (1) Reference air kerma rate in air $(\dot{K}_{air}(d_{ref}))_{air}$,
    defined by the ICRU (reports No. 38 and 58) as the air kerma rate in air at a reference distance d_{ref} of 1 m,
    corrected for air attenuation and scattering (unit: 1 μGy/h).

    The SI unit of the reference air kerma rate is Gy/s, but for the purposes of source specification it is more convenient to use μGy/h for LDR sources and μGy/s for HDR sources.

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13.2 PHOTON SOURCE CHARACTERISTICS
13.2.4 Source specification

- Specification of gamma ray sources (cont.):

(2) Air kerma strength S_K, defined by the AAPM as

$$S_K = (\dot{K}_{air}(d_{ref}))_{air} \times d_{ref}^2$$

The unit of air kerma strength is $\mu Gy \cdot m^2 \cdot h^{-1}$.

AAPM TG 43 recommends a shorthand notation with U
$1\ U = 1\ \mu Gy \cdot m^2 \cdot h^{-1} = 1\ cGy \cdot cm^2 \cdot h^{-1}$

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13.2 PHOTON SOURCE CHARACTERISTICS
13.2.4 Source specification

- Specification of gamma ray sources (cont.)

(4) Air kerma rate in air $(\dot{K}_{air}(d))_{air}$ at point P in air at a distance d from the source:

$$(\dot{K}_{air}(d))_{air} = \frac{A_{app}\Gamma_{AKR}}{d^2}$$

where

A_{app} is the apparent activity of the source in Bq
Γ_{AKR} is the air kerma rate constant given in $(\mu Gy \cdot m^2)/(GBq \cdot h)$
d is the distance from the source in m

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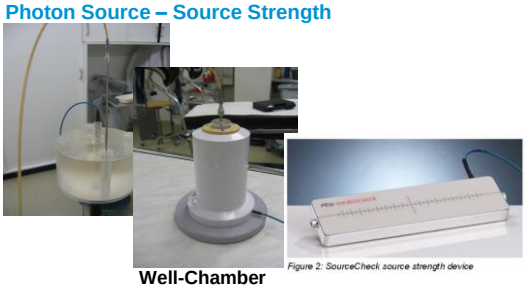
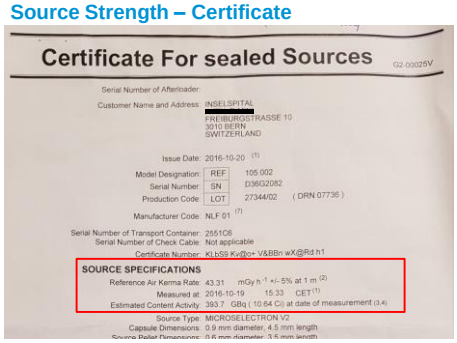
Photon Source – Source Strength



Well-Chamber

Figure 2: SourceCheck source strength device

Source Strength – Certificate



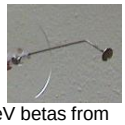
Certificate For sealed Sources G2-00025V

Serial Number of Afterloader:
Customer Name and Address: INSELSPITAL [redacted] FREIBURGSTRASSE 10 3010 BERN SWITZERLAND

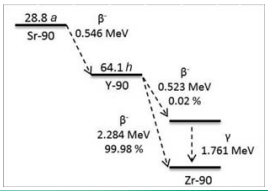
Issue Date: 2016-10-20 (1)
Model Designation: REF 105.002
Serial Number: SN D36G2082
Production Code: LOT 27344/02 (DRN 07736)
Manufacturer Code: NLF 01 (7)
Serial Number of Transport Container: 2551D8
Serial Number of Check Cable: Not applicable
Certificate Number: KLbS9 Kv@o+ V&BBn wX@Rd h1

SOURCE SPECIFICATIONS
Reference Air Kerma Rate: 43.31 mGy h^{-1} +/- 5% at 1 m (2)
Measured at: 2016-10-19 15:33 CET (1)
Estimated Content Activity: 393.7 GBq (10.64 Ci) at date of measurement (3,4)
Source Type: MICROSELECTRON V2
Capsule Dimensions: 0.9 mm diameter, 4.5 mm length

Beta sources - Strontium-90



- Bye product of nuclear fission
- Therapeutic radiation is primarily from 2.27 MeV betas from Y-90
- Suitable for treatment of superficial lesions, ocular lesions and coronary vessels
- Limited depth of penetration



13.2 BETA SOURCE CHARACTERISTICS
13.2.4 Source specification

- Specification of beta ray sources: Sr-90/Y-90
  - The recommended quantity for the specification of beta ray sources is the reference absorbed dose rate in water at a reference distance from the source.
  - The reference distance differs from one type of source to another and is generally between 0.5 mm and 2 mm from the source.
  - SGSMP recommendation #14 "Physical aspects of intravascular brachytherapy of the coronary arteries" recommends 2 mm and also includes quality assurance measures.
    http://www.sgsmp.ch/r14ivb-e.pdf

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Radiation Oncology Physics: A Handbook for Teachers and Students - 13.2.4 Slide 6 (30/163)

13.1 INTRODUCTION

Brachytherapy classification with respect to treatment duration:

- Temporary implant
  - Dose is delivered over a period of time that is short in comparison with the half-life of the sources.
  - Sources are removed when the prescribed dose has been reached.
- Permanent implant
  - Dose is delivered over the lifetime of the sources.
  - The sources undergo complete radioactive decay.

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Radiation Oncology Physics: A Handbook for Teachers and Students - 13.1 Slide 8 (10/163)

13.1 INTRODUCTION

Types of brachytherapy implants:

- Intracavitary: Sources are placed into a body cavity.
  Gynecological applications, rectum
- Interstitial: Sources are implanted into the tumor volume.
  HNO, lip, eyelid, mamma, rectum, prostate
- Surface plaque: Sources are loaded into a plaque which is brought into contact with a skin surface lesion or eye cornea
- Intraluminal: Sources are inserted into a lumen.
  Bronchus, oesophagus, HNO
- Intraoperative: Sources are brought surgically into or near the tumor volume.
  Single catheter or flabs
- Intravascular: Sources are brought intravascularly into a lesion or near a lesion.

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Radiation Oncology Physics: A Handbook for Teachers and Students - 13.1 Slide 7 (9/163)

13.1 INTRODUCTION

Brachytherapy classification with respect to dose rate:

- Low dose rate (LDR) (0.4 - 2 Gy/h)
- Medium dose rate (MDR) (2 - 12 Gy/h)
- High dose rate (HDR) (> 12 Gy/h)
- Pulsed dose rate (PDR): Simulation of a low dose rate (LDR) treatment (50-100cGy/h) by a series of short dose pulses separated by intervals of 1 hour to several hours

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Radiation Oncology Physics: A Handbook for Teachers and Students - 13.1 Slide 13 (15/163)

13.1 INTRODUCTION

Brachytherapy classification with respect to source loading:

- Hot loading
  The applicator is pre-loaded and contains radioactive sources at time of placement into the patient.
- Afterloading
  The applicator is placed first into the patient and the radioactive sources are loaded later
  - either by hand (manual afterloading)
  - or by machine (automatic remote afterloading)

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Radiation Oncology Physics: A Handbook for Teachers and Students - 13.1 Slide 9 (11/163)

13.1 INTRODUCTION

- Manual afterloading
  - Generally, the radiation sources are afterloaded manually into applicators or catheters that have been placed within the target volume. At the end of treatment the sources are removed, again manually.
  - Manual loading and removal of sources from the applicators or catheters result in some radiation exposure to the medical and support staff.

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13.1 INTRODUCTION

Remote afterloading

- To minimize radiation exposure to medical and support staff several computer driven remote afterloading systems have been developed.
- The use of remote afterloading machines offers several practical advantages over manual procedures, such as:
  - Increased patient treatment capacity.
  - Consistent and reproducible treatment delivery.
  - Reduced radiation exposure to staff.

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Brachytherapy – HDR Afterloading Systems

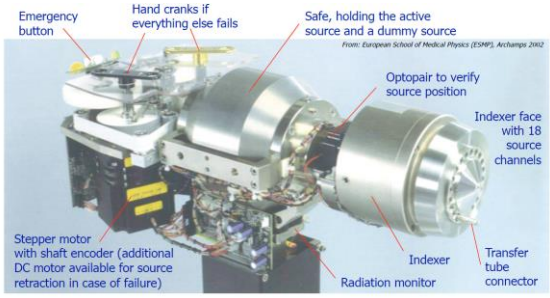
Flexitron (Elekta)

MultiSource
(Eckert & Ziegler BEBIG)

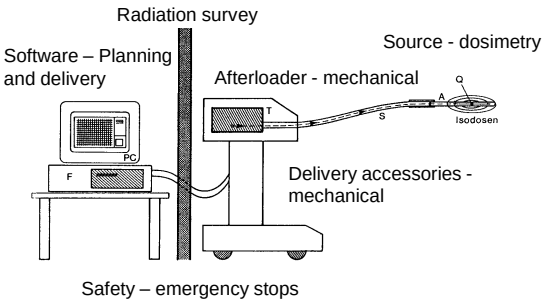
microSelectron (Elekta)

GammaMed (Varian)

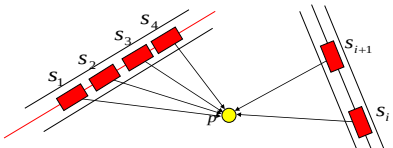
Brachytherapy – HDR Afterloading Systems



Brachytherapy – HDR Afterloading Systems



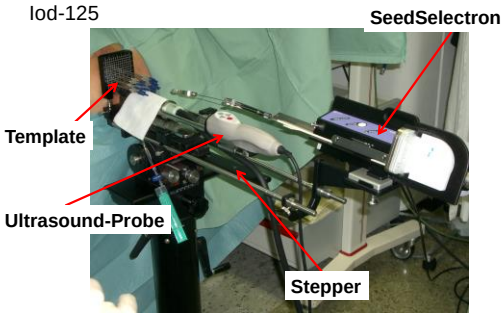
Brachytherapy – HDR Afterloading Systems



$$D_p = \dot{D}_p(s_1)\cdot t_{s_1} + \dot{D}_p(s_2)\cdot t_{s_2} + \dot{D}_p(s_3)\cdot t_{s_3} + \dot{D}_p(s_4)\cdot t_{s_4} + \cdots \dot{D}_p(s_i)\cdot t_{s_i}$$

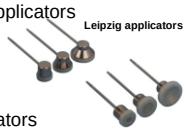
Brachytherapy – LDR Afterloading Systems

Iod-125

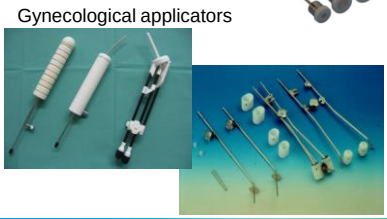


Brachytherapy - Applicators

Surface applicators



Gynecological applicators



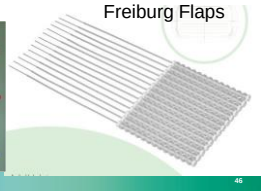
Brachytherapy - Applicators

Needles

Catheters

Breast applicators

Freiburg Flaps



Dose distribution around a sources

Dose calculation around radioactive sources in brachytherapy can be devided in three main categories:

- Historical approaches to dose calculation (may be used for quick checks and verification of treatment plans):
  - Point source calculation based on air kerma in air
  - Line source calculation based on air kerma in air
- AAPM TG43 Formalism
- Model based dose calculation algorithms (MBDCA)

13.5 DOSE DISTRIBUTIONS AROUND SOURCES

13.5.2 Other calculation methods for point sources

- If source is calibrated in terms of reference air kerma rate in air $(\dot{K}_{air}(d_{ref}))_{air}$, the air kerma rate in air at distance d is given by

$$(\dot{K}_{air}(d))_{air} = (\dot{K}_{air}(d_{ref}))_{air} \times (d_{ref}/d)^2$$

- Absorbed dose rate to water $\dot{D}_{wat}(d)$ is now given as

$$\dot{D}_{wat}(d) = (\dot{K}_{air}(d_{ref}))_{air} \times M(d) \times (\mu_{tr}/\rho)_{air}^{wat} \times (1-\bar{g}) \times (d_{ref}/d)^2$$

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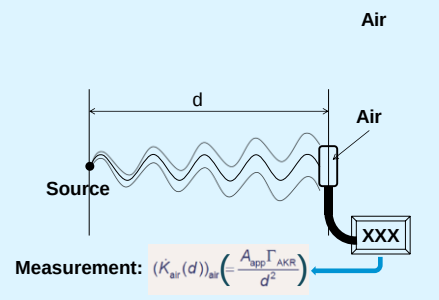
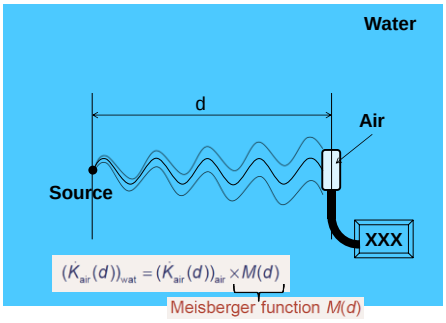
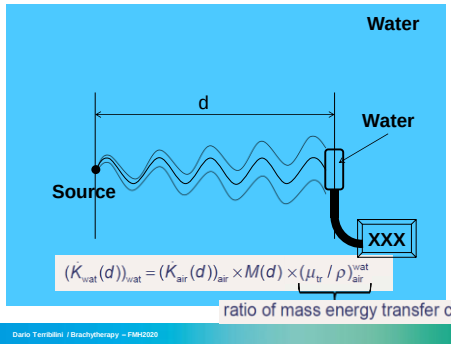
Dose distribution around sources – Point Source



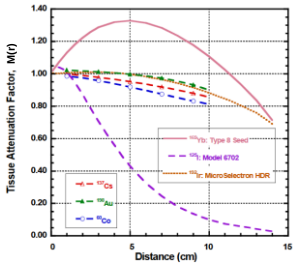
Dose distribution around sources – Point Source



Dose distribution around sources – Point Source

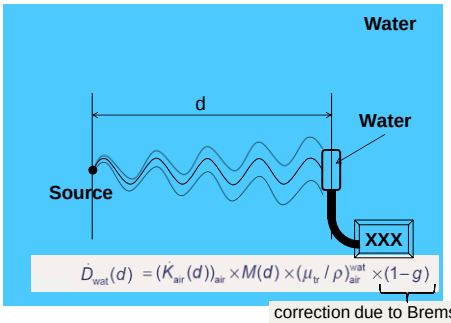


Dose distribution – Tissue attenuation factor M(d)



For energies >300keV the attenuation in tissue is compensated by scatter build up of dose.
Tissue attenuation is very significant for low photon energies (<30keV)

Dose distribution around sources – Point Source



$$\dot{D}_{wat}(d) = (\dot{K}_{air}(d))_{air} \times M(d) \times (\mu_{tr}/\rho)_{air}^{wat} \times (1-g)$$

correction due to Bremsstrahlung

Dose distribution around a sources

Ratio of mass energy transfer coefficients $(\mu_{tr}/\rho)_{air}^{wat}$:

- with photon energies above 200 keV the ratio is essentially constant at 1.11
- for iodine-125 and palladium-103 the ratio is 1.01.

The radiation fraction (Bremsstrahlung) is generally ignored because of its small magnitude (less than 0.3%) for the radionuclides used in brachytherapy.

The Meisberger function M(d) corrects for absorption and scattering in water.

13.5 DOSE DISTRIBUTIONS AROUND SOURCES
13.5.3 Linear (line) sources

- Dose rate distributions around linear (line) brachytherapy sources can be calculated using the Sievert integral, introduced by Sievert in 1921.
- For purposes of dose distribution calculation, linear sources are assumed to consist of a number of small elementary point sources, each point source contributing to the total dose at the point of interest P.

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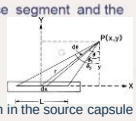
13.5 DOSE DISTRIBUTIONS AROUND SOURCES
13.5.3 Linear sources

- Dose rate in water around filtered line source

$$\dot{D}_{wat} = \frac{A\Gamma_{AKR}}{Lh}\left\{\int_0^{\theta_2} e^{-\frac{\mu t}{\cos\theta}} M(d,\theta)d\theta - \int_0^{\theta_1} e^{-\frac{\mu t}{\cos\theta}} M(d,\theta)d\theta\right\}\left(\frac{\mu_{tr}}{\rho}\right)_{air}^{wat}(1-\bar{g})$$

- $M(d,\theta)$ is the absorption and scatter correction varying over the source length.
- d is the distance between the source segment and the point of interest P.
- $\bar{g}$ is the radiation fraction.
- t is the thickness of the source capsule
- μ is the attenuation coefficient for photon in the source capsule material



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13.5 DOSE DISTRIBUTIONS AROUND SOURCES
13.5.3 Linear sources

- Sievert integral $\int_0^{\theta} e^{-\frac{\mu t}{\cos\theta}} d\theta$ is used in computing dose distributions for filtered brachytherapy line sources.
- The integral is named after Rolf Sievert, Swedish medical physicist, who developed it in 1921.
- The Sievert integral accounts for photon attenuation in the source capsule of the brachytherapy line source.
- For $\theta < 0.35$ radian (20°) the following approximation can be used

$$\int_0^{\theta_2} e^{-\frac{\mu t}{\cos\theta}} d\theta \approx \theta e^{-\mu t}$$

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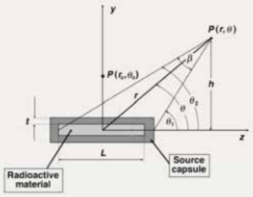
13.5 DOSE DISTRIBUTIONS AROUND SOURCES
13.5.1 AAPM TG 43 algorithm

- The dose distribution is described in terms of a polar coordinate system with its origin at the source centre.



r is the distance from the origin to the point of interest $P(r,\theta)$

θ is the angle with respect to the long axis of the source

Point $P(r_0,\theta_0)$ is the reference point that lies on the transverse bisector of the source at a distance of 1 cm from the origin ($r_0 = 1$ cm and $\theta_0 = \pi/2$)

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13.5 DOSE DISTRIBUTIONS AROUND SOURCES
13.5.1 AAPM TG 43 algorithm

The dose rate at point-of-interest $P(r,\theta)$ in water is written as:

$$\dot{D}(r,\theta) = S_K \Lambda \frac{G(r,\theta)}{G(r_0,\theta_0)} g(r) F(r,\theta)$$

- r is the distance (in cm) from the origin to the point-of-interest P
- θ is the angle between direction of radius vector r and the long axis of the source
- θ_0 defines the source transverse plane and is equal to $\pi/2$ radians
- S_K is the air-kerma strength of the source ($\mu Gy \cdot m^2 \cdot h^{-1}$)
- Λ is the dose rate constant in water
- $G(r,\theta)$ is the geometry factor
- $g(r)$ is the radial dose function
- $F(r,\theta)$ is the anisotropy function

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13.5 DOSE DISTRIBUTIONS AROUND SOURCES
13.5.1 AAPM TG 43 algorithm

- The AAPM TG 43 brachytherapy dosimetry protocol introduced new and updated quantities, such as:
  - Air kerma strength (as defined previously)
  - Dose rate constant to account for effects of source geometry and scattering in water surrounding the source on absolute dose rate at reference point (perpendicular over source centre)
  - Geometry factor to account for the deviation from the distance square law due to the source geometry (in three dimensions)
  - Radial dose function to account for the effects of attenuation and scatter in water on the transverse plane (excluding effects included in the geometry factor)
  - Anisotropy function to account for the anisotropy of the dose distribution, especially the effect of self absorption in and near the axis of the line source
  - (Anisotropy factor for simplified calculations, ignoring the shape of the anisotropy, and "averaging it out" in the absolute dose calculations: often used for 3-D implants with many sources of varying orientation, e.g. prostate implants)

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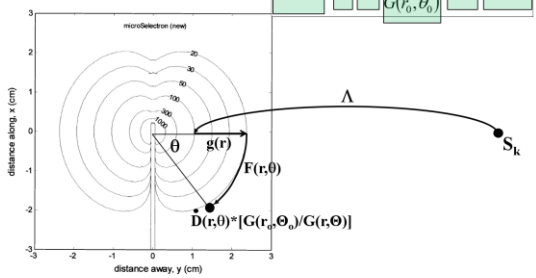
AAPM TG 43 – Formalismus

$$\dot{D}(r,\theta) = S_k \cdot \Lambda \cdot \frac{G(r,\theta)}{G(r_0,\theta_0)} \cdot g(r) \cdot F(r,\theta)$$



AAPM TG 43 – …some numbers for a Ir-192 Source

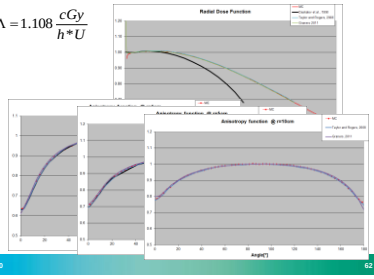
Kerma Strength: $S_k = 30'000 \frac{\mu Gy \bullet m^2}{h} \left(= 3 \frac{cGy * m^2}{h} \right)$ $\quad 1U = 1 \frac{\mu Gy \bullet m^2}{h}$

(Typical value after source replacement)

Dose Rate Constant: $\Lambda = 1.108 \frac{cGy}{h * U}$

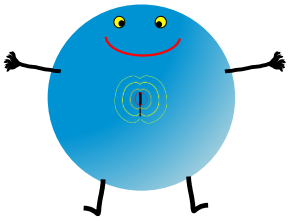
Radial Dose Function:

Anisotropy Function:



AAPM TG 43 – Assumptions & Limitations

- Dose calculation in water
  - no material heterogeneities within the body
  - no applicators
  - no shieldings
  - no source interplay
- Infinite patient
  - no phantom size effect
- Azimuthal symmetry



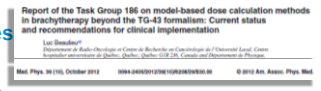
AAPM TG 43 – Limitations

TABLE I. Sensitivity of commonly treated anatomic sites to dosimetric limitations of the current brachytherapy dose calculation formalism. Items flagged as "Y" indicate the authors opinion that significant differences between administered and delivered dose are possible due to the highlighted dosimetric limitation.

Anatomic site	Source energy	Absorbed dose	Attenuation	Shielding	Scattering	Beta/kerma dose
Prostate	High	N	N	N	N	N
	Low	Y	Y	Y	N	N
Breast	High	N	N	N	Y	N
	Low	Y	Y	Y	N	N
GYN	High	N	N	Y	N	N
	Low	Y	Y	N	N	N
Skin	High	N	N	Y	Y	N
	Low	Y	N	Y	Y	N
Lung	High	N	N	N	Y	Y
	Low	Y	Y	N	Y	N
Penis	High	N	N	N	Y	N
	Low	Y	N	N	Y	N
Eye	High	N	N	Y	Y	Y
	Low	Y	Y	Y	Y	N

Rivard et al., Med Phys. 36, 2009.

Alternative Approaches


Report of the Task Group 186 on model-based dose calculation methods in brachytherapy beyond the TG-43 formalism: Current status and recommendations for clinical implementation

Luc Beaulieu

Med. Phys. 39 (10), October 2012 © 2012 Am. Assoc. Phys. Med.

The goal is to take
- patient inhomogeneities
- patient shape
- source interplays
- effects of applicators and shieldings

into account which are ignored by the AAPM TG 43 protocol

- ➢ Analytical Models (Convolution/Superposition, CC)
- ➢ Full Monte Carlo Simulations
- ➢ Deterministic solutions of the transport equations (LBTE)

AAPM TG 186 – MBDCA

- **ACE (Collapsed Cone) of ELEKTA**
- **Full Monte Carlo**
- **Accuros (Boltzmann Solver) of Varian**

MBDCA – Collapsed Cone / PSS Formalism

Dose is deposited locally through primary electrons set in motion by a photon interaction and a large fraction through scattered components.

➔ Separation of the primary dose and scattered dose components:

$$D = D_{prim} + D_{1sc} + D_{msc}$$

Russell et al., Med. Phys. 32, 2005.

PSS : Primary & Scatter Separation

MBDCA – Collapsed Cone

$$D = D_{prim} + D_{1sc} + D_{msc}$$

D_{prim}

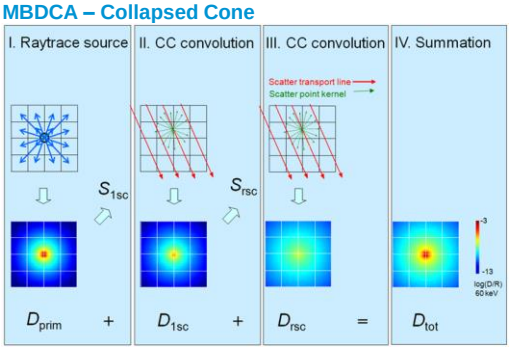
- ➔Phantom size independent
- ➔Energy dependent
- ➔Source geometry dependent
- ➔Depends on local mass attenuation coefficient (μ)

$D_{1sc} + D_{msc}$

- ➔Depend on phantom size
- ➔Energy dependent
- ➔Source geometry dependent
- ➔ Depend on primary dose (D_{prim})

Russell et al., Med. Phys. 32, 2005.

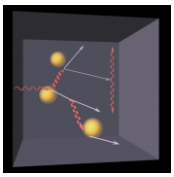
MBDCA – Collapsed Cone



Ahnesjö, Dreiländertagung 2007 Bern

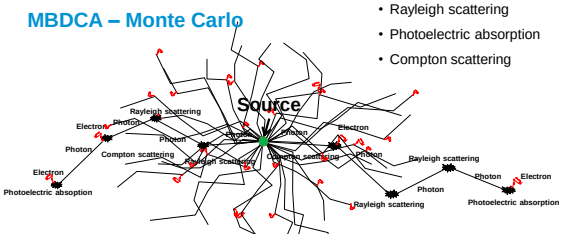
AAPM TG 186 – MBDCA

- ACE (Collapsed Cone)
- **Full Monte Carlo**
- Accuros (Bolzmann Solver) of Varian



MBDCA – Monte Carlo

- Rayleigh scattering
- Photoelectric absorption
- Compton scattering



Dose per simulated history ~10^{-12} Gy (Ir-192 point source)
➔ For 1 Gy about 10'000'000'000'000 histories needed!!

"Only" ~1'000'000'000 histories are simulated for statistically acceptable results
➔ Monte Carlo provide the user with an estimate of the solution.

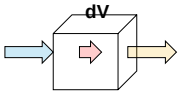
AAPM TG 186 – MBDCA

- ACE (Collapsed Cone) of ELEKTA
- Full Monte Carlo
- **Accuros (Boltzmann Solver) of Varian**

MBDCA – Boltzmann Solver

An alternative approach is to solve the steady state Boltzmann transport equation in a Cartesian coordinate system:

Streaming operator	Collision operator	Scattering source	External source
$\hat{\Omega} \cdot \vec{\nabla}\Psi(\vec{r}, E, \hat{\Omega})$	$+\sigma_t(\vec{r}, E)\Psi(\vec{r}, E, \hat{\Omega})$	$= Q^{\mathrm{scat}}(\vec{r}, E, \hat{\Omega})$	$+ Q^{\mathrm{ex}}(\vec{r}, E, \hat{\Omega})$
Number of particles flowing into a volume dV , minus the number of particles flowing out of dV for particles travelling in a direction dΩ about Ω with energy E about dE	Number of particles removed from the volume by absorption or scattering	Number of scattered particles entering the volume	Brachytherapy sources



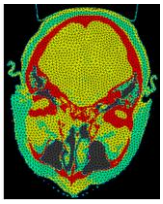
Ψ is the angular energy fluence at position r = (x, y, z), with energy E, and direction Ω = (μ, η, ζ).

Gifford et al., Phys. Med. Biol. 51, 22, 2006.

MBDCA – Boltzmann Solver

The most common deterministic approach has been historically known as 'discrete ordinates':

➔ Discretization in space (finite element or finite difference), angle (discrete ordinates), and energy (multi-group cross sections)



The challenge is to solve this equation for every sub-volume (dV) of the total volume (patient).

Dosimetry Systems & Dose Calculation Procedures

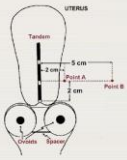
Pre–calculated dose distributions (atlases)

- Gynecology
  - Manchester
  - …
- Interstitial brachytherapy
  - Patterson-Parker (Manchester) system
  - Quimby (Memorial) system
  - Paris system
  - …
- Other (eye plaques, ect)

Dosimetry Systems & Dose Calculation Procedures

Gynecology (Manchester)

- Manchester system is characterized by doses to four points: point A, point B, bladder point, and rectum point.
- Duration of the irradiation is based on the dose rate at point A, which is located 2 cm superior to the cervical orifice (os) and 2 cm lateral to the cervical canal.
- Point B is defined 3 cm laterally to point A when the central canal is not displaced.



If the tandem displaces the central canal, point A moves with the canal, but point B remains fixed at 5 cm from the midline.

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.1 Gynaecology

- The gynecological dosimetry system recommended by the ICRU (Report 38) relates the dose distribution to the target volume rather than to a specific point.
- The report identifies a dose level of 60 Gy as the appropriate reference dose level for LDR treatments. This results in a requirement to specify the dimensions of the pear-shaped 60 Gy isodose reference volume.

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13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.2 Interstitial brachytherapy

- Patterson-Parker (Manchester) system
  - The aim of this system is to deliver a uniform dose (within ±10% of the prescribed dose) throughout the target volume.
  - The sources are distributed non-uniformly, following certain rules, with more of the source strength concentrated in the periphery of the target volume.

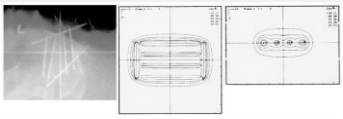

Fig 6.2: Manchester System for application of radioactive sources with different loading. Fig A shows the localisation film. Fig B and C give the distribution of dose rate for a single-plane implant with iridium wires of unequal linear activity in order to ensure dose uniformity throughout the implanted region. Wires 1, 4, 5 and 6 (peripheral) contain a linear activity of 60 MBq per cm; wires 2 and 3 contain a linear activity of 37MBq per cm. Wires 1, 2, 3 and 4 are 6 cm long; wires 5 and 6 are 3.5 cm long. Fig B gives the dose rates in the plane containing the wires. Fig C in a perpendicular plane. (From Wambersie and Battermann [115])

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13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.2 Interstitial brachytherapy

- Patterson-Parker tables
  - Single plane: The source arrangement treats a 1 cm thick slab of tissue. The prescribed dose is on a parallel plane 0.5 cm away from the source plane.
  - Double plane is used to treat slabs of tissue with thick-ness between 1 cm and 2.5 cm. The required total source strength is equally divided between the two planes.

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13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.2 Interstitial brachytherapy

- Paris system
  - The Paris system is used for single and double plane implants.
  - The general rules for the Paris system are as follows:
    - Sources must be linear and their placement must be parallel.
    - Centres of all sources must be located in the same (central) plane.
    - Linear source strength (activity) must be uniform and identical for all sources in the implant.
    - Adjacent sources must be equidistant from one another.

Fig 6.3 : Iridium-192 wire implant according to the Paris system (single-plane implant). The wires are of equal linear activity, parallel, and arranged in such a way that their centres are in the same plane perpendicular to the direction of the wires (i.e. the central plane, see Fig 6.4).
(From Wambersie and Battermann [115])

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Dosimetry Systems & Dose Calculation Procedures

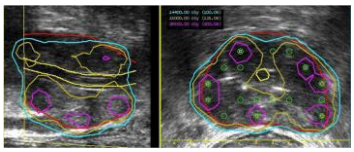
Personalized/Computerized Treatment Planning

- Source/implant/applicator localization:
  - Projections
  - Computerized tomography (CT) scanning
  - Ultrasound scanning (US)
  - Magnetic resonance imaging (MRI)
- Optimization
  - Time/Activity
  - Position

Dose Calculation Procedures – LDR

Permanent prostate implants (LDR)
- Seed activity
- Seed positions

Choose seed locations to meet some objectives
- Target coverage
- Dose uniformity
- OAR sparing



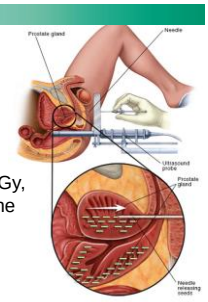
Brachytherapy – LDR

Iod-125

Low Dose Rate (LDR)*: <1 Gy/h*

In order to achieve a total dose of ~144Gy, the radioactive emitter must remain in the tissue / organ until it has completely decayed

➔ Permanent implant
➔ The patient can go home as long as the local dose is 1m <5µSv/h ist



Dose Calculation Procedures – HDR

Stepping source (HDR/PDR) brachytherapy offers two degrees of freedom to optimize the dose distribution:
- Dwell position
- Dwell time

There are two modes of optimization on the activated dwell positions:
- Forward optimization
- Inverse optimization

Dose Calculation Procedures – HDR

The following forward optimization methods are implemented:
- Manual dwell weights/times optimization
- Geometrical optimization
- Optimization on dose points
- Graphical optimization

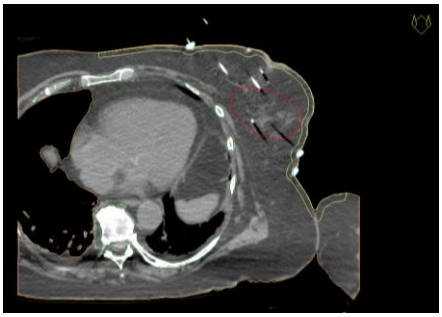
The following inverse optimization methods are implemented:
- Inverse Planning by Simulated Annealing (IPSA)
- Hybrid Inverse Planning Optimization (HIPO)

Brachytherapy – Mamma Ca

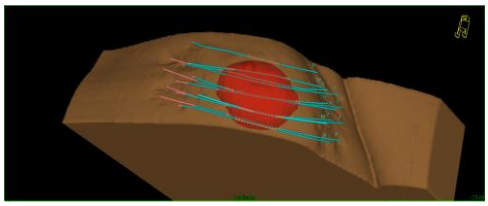
Mamma Ca: Interstitial brachytherapy, partial breast radiation

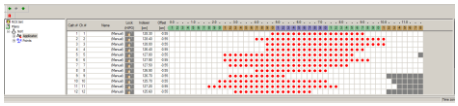
Planning – CT acquisition

Planning – Contouring

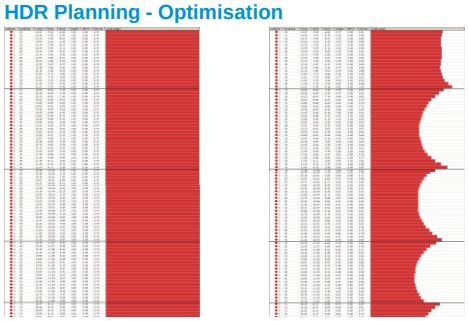


HDR Planning - Activation

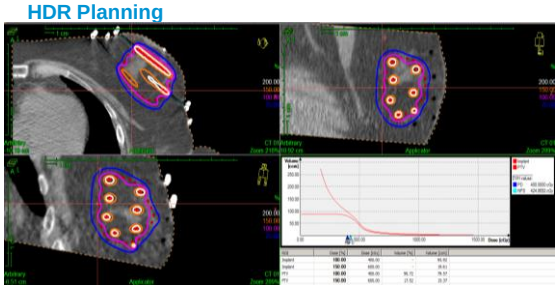




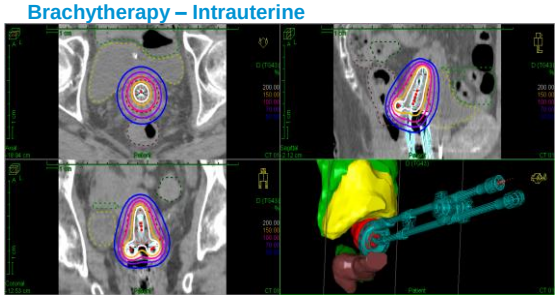
HDR Planning - Optimisation



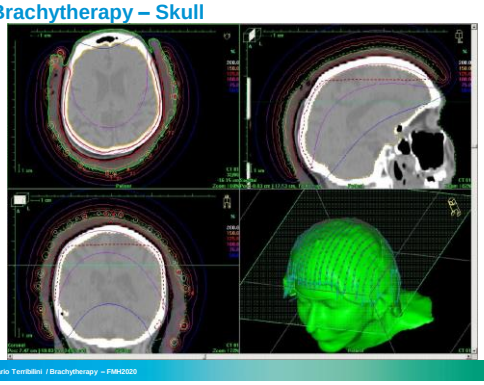
HDR Planning



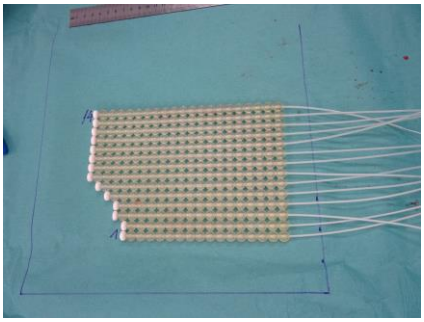
Brachytherapy – Intrauterine



Brachytherapy – Skull



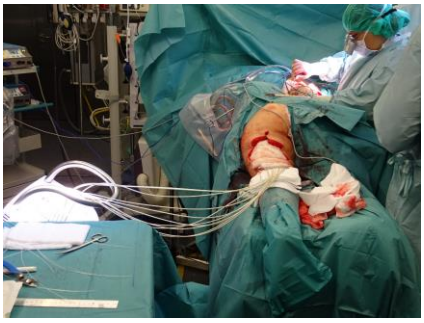
Brachytherapy – Intraoperative Brachytherapy



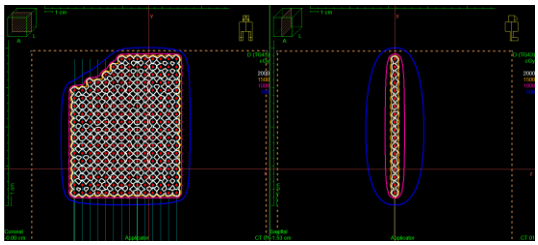
Brachytherapy – Intraoperative Brachytherapy

Brachytherapy – Intraoperative Brachytherapy

Brachytherapy – Intraoperative Brachytherapy



Brachytherapy – Intraoperative Brachytherapy



Brachytherapy – Intraoperative Brachytherapy

At the Inselspital IORTs are carried out:

- Tumors of the gastrointestinal tract
- Sarcomas
- Gynecological tumors
- Recurrent tumors

Prescription dose: 10 Gy @ 5mm tissue depth

13.4 DOSE SPECIFICATION AND REPORTING

- Using standardized and uniform methodology, the ICRU Reports 38 and 58 recommend the minimum information that must be reported when performing brachytherapy treatments, such as:
  - Description of the implant.
  - Definition of the volume of interest.
  - Prescription dose.
  - Delivered dose.
  - Reference air kerma rate in air in cGy/h at 1 m.

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13.4 DOSE SPECIFICATION AND REPORTING
13.4.1 Intracavitary treatments

- Data recommended in the ICRU Report 38 for reporting of gynaecological brachytherapy are:
  - Description of technique.
  - Reference air kerma rate in air in cGy/h at 1 m.
  - Time/dose pattern.
  - Description of the reference volume.
  - Dose at reference points (bladder, rectum, pelvic wall, lymphatic trapezoid).
  - Dimensions of the pear shaped 60 Gy isodose reference volume….for LDR!

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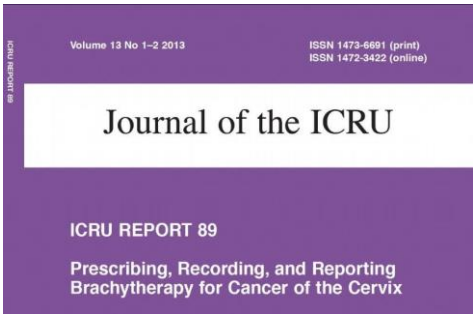
Gynecological Brachytherapy - ICRU 89



Gynecological Brachytherapy - ICRU 89

Table of Contents

Gynecological Brachytherapy - ICRU 89

Need for Common Terminology According to ICRU Reports on Proton Treatment and IMRT

- **Planning aim dose**
  - Set of dose and dose/volume constraints for a treatment
- **Prescribed dose**
  - Finally accepted treatment plan (which is assumed to be delivered to an individual patient)
- **Delivered dose**
  - Actually delivered dose to the individual patient

Chapter 8

Gynecological Brachytherapy - ICRU 89

Level Concept

Concepts and terminology for prescribing

Reporting and recording in a level concept:

- **Level 1 – *Minimum standard for reporting***
- **Level 2 – *Advanced standard for reporting***
- **Level 3 – *Research-oriented reporting***

Gynecological Brachytherapy - ICRU 89

Level 1 – *Minimum Standard for Reporting*

- Comprehensive clinical gynecologic examination
- Volumetric imaging (MRI, CT, US, PET CT) at time of diagnosis and BT
- FIGO/TNM stage
- Baseline morbidity and QoL assessment
- Schematic 3D documentation on a clinical diagram indicating dimensions and volumes for:
  - GTV_{init} (GTV at diagnosis)
  - GTV_{res} (GTV at brachytherapy)
  - CTV_{HR} (GTV_{res} (plus residual pathologic tissue plus whole cervix)
  - (CTV_{IR}: GTV_{init} and CTV_{HR} plus safety margin if used for prescription)

BrachyNext – Working Together to Shape the Future of Brachytherapy

Gynecological Brachytherapy - ICRU 89

Level 1 – *Minimum Standard for Reporting*

Dose reporting:

- TRAK
- Point A dose
- Recto-vaginal reference point dose
- $D_{0.1cm^3}$,D_{2cm^3} for bladder, rectum

  or

  Bladder reference point for radiographs

Chapter 8 and Chapter 10

BrachyNext – Working Together to Shape the Future of Brachytherapy

Gynecological Brachytherapy - ICRU 89

Level 2 – *Advanced Standard for Reporting*

All that is reported in level 1 plus:

3D delineation of volumes (on volumetric images with applicator and on clinical diagrams):

- GTV_{res}
- CTV_{HR}
- (CTV_{IR} if used for prescription)
- With maximum width, height, thickness and with volume

Chapter 5

BrachyNext – Working Together to Shape the Future of Brachytherapy

Gynecological Brachytherapy - ICRU 89

Level 2 – *Advanced Standard for Reporting*

All that is reported in level 1 plus:

Dose reporting for defined volumes:

- D_{98}, D_{90}, D_{50} for CTV_{HR}
- (D_{98}, D_{90} for CTV_{IR} if used for prescription)
- D_{98} for GTV_{res}
- D_{98} for pathological lymph nodes

Chapter 8

BrachyNext – Working Together to Shape the Future of Brachytherapy

Gynecological Brachytherapy - ICRU 89

Level 2 – *Advanced Standard for Reporting*

All that is reported in level 1 plus:

Dose reporting OARs:

- Bladder reference point dose
- $D_{0.1cm^3}$,D_{2cm^3} for sigmoid*
- D_{2cm^3} bowel (if fixed)*
- Intermediate and low dose parameters in bladder, rectum, sigmoid, bowel (e.g. V_{25Gy}, V_{35Gy}, V_{45Gy} or $D_{98\%}$, $D_{50\%}$, $D_{2\%}$)
- Vaginal point doses at level of sources (lateral at 5 mm)**
- Lower and mid vagina doses (PIBS, PIBS ±2cm)**

Chapter 8

BrachyNext – Working Together to Shape the Future of Brachytherapy

13.4 DOSE SPECIFICATION AND REPORTING

13.4.2 Interstitial treatments

- Data recommended in the ICRU Report 58 for reporting of interstitial implant treatments are:
  - Description of the clinical target volume.
  - Sources, technique, and implant time.
  - Prescription dose.
  - Reference air kerma rate in air in cGy/h at 1 m.
  - Description of the dose distribution.
  - Description of the high and low dose region and dose uniformity indices.
  - Dose-volume histograms.

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13.4 DOSE SPECIFICATION AND REPORTING
13.4.2 Interstitial treatments

- As far as dose distribution is concerned, four different dose related quantities are to be reported to adequately describe an implant treatment:
  - Total reference air kerma.
  - Mean central dose representing the plateau dose region inside the target volume.
  - Minimum dose, important for tumour control.
  - High dose regions exceeding 150% of the mean central dose and low dose regions that are below 90% of the peripheral dose.

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References on dose specification & reporting

- ICRU 38 (1985): Dose and Volume Specification for Reporting Intracavitary Therapy in Gynaecology
- ICRU 89 (2013): Prescribing, Recording, and Reporting Brachytherapy for Cancer of the Cervix
- ICRU 58 (1997): Dose and Volume Specification for Reporting Interstitial Therapy
- American Brachytherapy Society (ABS) Recommendations for Transperineal Permaent Brachytherapy of Prostate Cancer (IJROBP 1999)
- SGSMP-Bericht 18 (1996): Dosis- und Volumenspezifikationen zur Dokumentation in der Brachytherapie
- www.estro.org/about/governance-organisation/committees-activities/gec-estro-handbook-of-brachytherapy
  - ➔ Reporting in Brachytherapy: Dose and Volume Specification

Thank you

…Questions?

Clinical Use and Dosimetry Systems

Application types

- Linear arrangements (vaginal cylinder, rectum, oesophagus, bronchus [one applicator only], peripheral vessels)
- Gynaecological applicators (fixed or adjustable geometry)
- Bronchus treatments with more than a single applicator
- Interstitial applications (head&neck, mamma)
  - LDR
  - HDR
- Prostate:
  - LDR (permanent seeds)
  - HDR (Afterloading)
- Intraoperative applications (individual needles, flab method)
- Eye plaques

Seelentag, 2009

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS

13.3.5 Eye plaques

- Intraocular melanoma is the most common primary malignant eye tumour in adults, originating mostly in the choroid (choroidal melanoma).
- Traditional treatment was enucleation (surgical eye removal).

- More recent treatment approaches rely on radiotherapy:
  - External beam radiotherapy with high energy x rays or charged particles.
  - Brachytherapy with temporary implants based on radioactive seeds loaded onto an eye plaque.

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13.3 CLINICAL USE AND DOSIMETRY SYSTEMS

13.3.5 Eye plaques

- Brachytherapy treatment
  - Eye plaque loaded with radioactive seeds is applied externally to the scleral (outer) eye surface over the tumour base.
  - Radiation with appropriate dose is intended to eliminate tumour cells without causing anatomical or functional damage to normal ocular tissues.

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13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.5 Eye plaques

- Brachytherapy treatment with eye plaques
  - Most commonly used seeds are iodine-125 seeds with typical activities of the order of 1 mCi.
  - The number of seeds per plaque ranges from 7 to 24 for plaque diameters of 12 to 20 mm.
  - Typical treatment dose rates are of the order of 1 Gy/h and typical prescription doses are of the order of 100 Gy.

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13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.5 Eye plaques

- Brachytherapy treatment with eye plaques
  - Most commonly used seeds are iodine-125 seeds with typical activities of the order of 1 mCi.
  - A less common brachytherapy approach is based on beta emitting sources, such as strontium-90/ittrium-90 and, more recently, ruttenium-106

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13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.6 Intravascular brachytherapy

- Application of radiation (using temporary or permanent implant) after treatment of arterial stenosis with angio-plasty and stent placement has been proven useful in preventing re-stenosis.
- Restenosis is the formation of scar tissue in an artery within 6 months following angioplasty, occurring in about 40% of angioplasty patients.

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13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.6 Intravascular brachytherapy

- Important characteristics of intravascular treatment are:
  - Type of source: electronic x ray, gamma ray, electron, positron
  - Physical form of radionuclide: wire, seed, pellet, metallic stent
  - Method of radiation delivery:
    - Manual or remote afterloading;
    - Syringe and inflatable balloon;
    - Radioactive stent
  - Radionuclide
    - For use in afterloading: iridium-192; ittrium-90; strontium-90/ittrium-90.
    - For use in inflatable balloon: xenon-133; rhenium-186; rhenium-188
    - For use in radioactive stent: phosphorus-32; vanadium-48

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