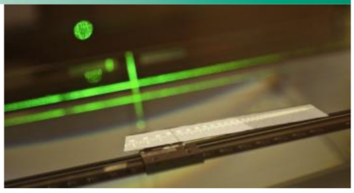
BRACHYTHERAPY

Dario Terribilini

INSELSPITAL
UNIVERSITÄTSSPITAL BERN
HOPITAL 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, Inselspital – University of Berne

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Overview

- Introduction
- Isotopes
- Techniques
- Planning Techniques
- Dose Calculation

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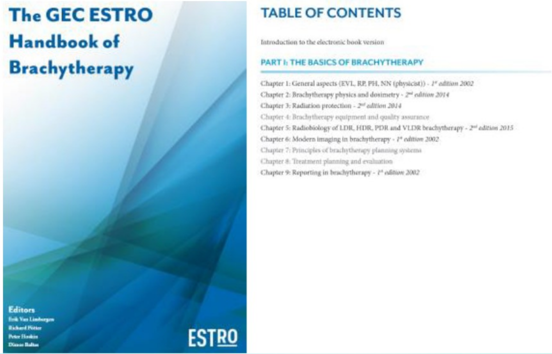

The GEC ESTRO Handbook of Brachytherapy

Editors
Erik Van Limbergen
Richard Pötter
Peter Hoskin
Dimos Baltas

ESTRO

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Chapter 3: Radiation protection - *2nd edition 2014*
Chapter 4: Brachytherapy equipment and quality assurance
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https://www.iaea.org/publications

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 IAEA experts, as teaching material during training events, 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
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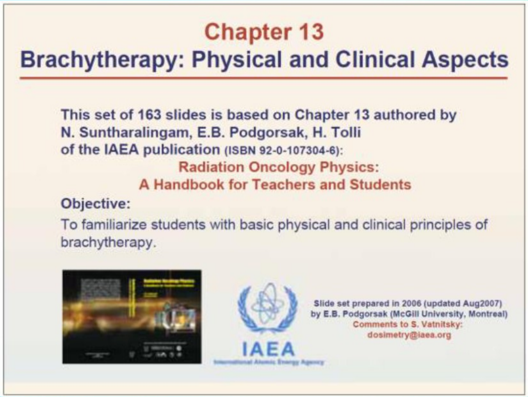


Chapter 13
Brachytherapy: Physical and Clinical Aspects

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.

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

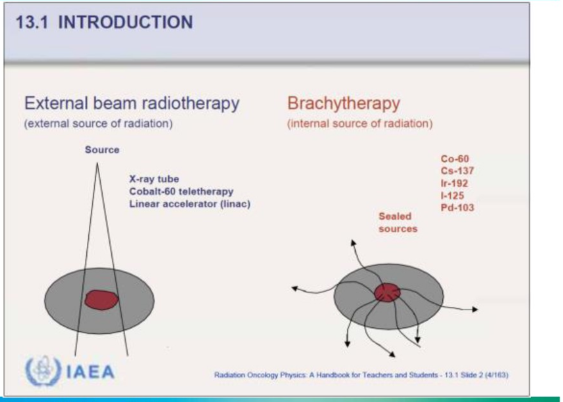
Introduction

Brachytherapy

Greek = close, short → treatment

Radiotherapy form in which a sealed radiation source is placed within or near to the region to be irradiated in the body:

- Radiation affects only a very limited area around the radiation source.
- Radiation exposure for healthy tissue located far away from the radiation sources is greatly reduced.
- Hypofractionation (higher single doses, several times daily)
- Radiation sources retain their exact position with respect to the tumor, even if the patient is moving or if there is a displacement of the tumor within the body during the treatment.



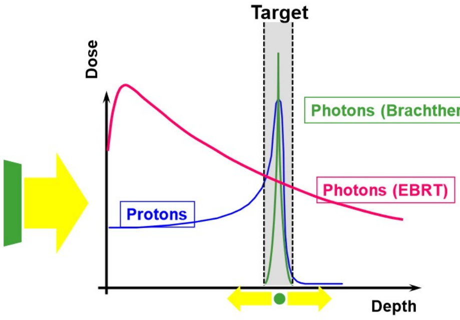
13.1 INTRODUCTION

External beam radiotherapy
(external source of radiation)

Brachytherapy
(internal source of radiation)

Radiation Oncology Physics: A Handbook for Teachers and Students - 13.1 Slide 2 (4/163)

Introduction – Photons vs Protons



Introduction – Brachytherapy vs EBRT

Advantages of Brachytherapy

- Highly localized dose delivery to the target
- Sharp dose fall-off outside the target with good sparing of the surrounding normal tissue leading to less side effects
- Very conformal form of radiotherapy
- Reduction of inter-fraction setup variability
- Shorter treatment time

Disadvantages of Brachytherapy

- For well localized and small tumors
- Team work needed
- Skills in interventional brachytherapy
- Invasive

Introduction – Types of Brachytherapy

Brachytherapy can be categorized in many ways:

- Type of emission
- Duration of the implant
- Location of the implant
- Dose rate
- Type of loading

Brachytherapy sources – Type of emission

Photon sources

- Emission of γ rays through γ decay and/or characteristic x-rays through electron capture and internal conversion. Examples: ^{60}Co, ^{137}Cs, ^{192}Ir, ^{125}I, ^{103}Pd, etc.

Beta sources

- Emission of electrons through beta source decay. Examples: ^{90}Sr/^{90}Y, ^{106}Ru, etc.

Alpha sources

- Emission of α particle through α decay. Example: ^{224}Ra

Neutron sources

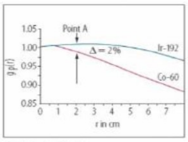
- Emission of neutrons following spontaneous nuclear fission. Example: ^{252}Cf

Miniature x-ray sources

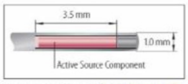
Photon Source Characteristics – Physics

The dose delivered with brachytherapy sources depends on:

- Photon energy spectrum
- HVL
- Half-life
- Specific activity
- Source strength
- Inverse square law

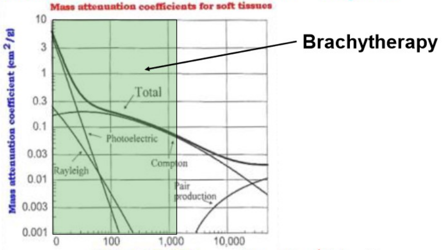


Radial Dose Rate Function



Miniaturised Co-60 Source for HDR afterloading

Photon Source Characteristics – Physics



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

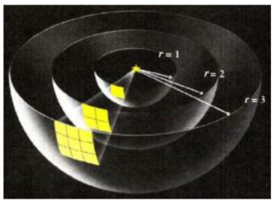
Photoelectric effect ($\tau_{photo} \sim Z^{\sim 4} E_{\gamma}^{-3}$) Pair production

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

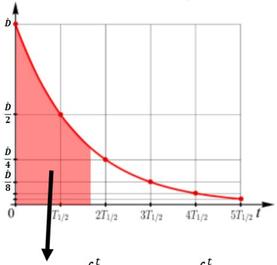
$\lambda = \frac{ln2}{t_{½}}$, and $t_{½}$ is the half-life of the radionuclide

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.



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

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

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

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

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

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

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

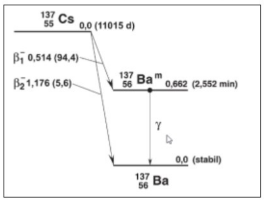
Photon Sources

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
^{125}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

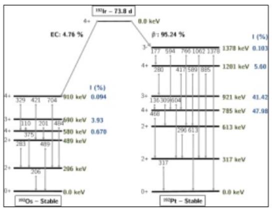
Cesium 137, a fission byproduct, is a popular radium substitute because of its 30-year half-life.

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,γ)^{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:

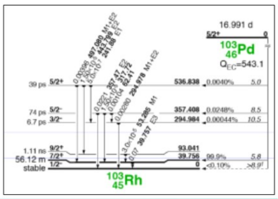
- By neutron activation of ^{102}Pd: ^{102}Pd(n,γ)^{103}Pd. (^{102}Pd occurs only at 0.9% level)
- By nuclear reaction with a proton beam on ^{103}Rh:
  ^{103}Rh(p,n)^{103}Pd. (natural abundance of ^{103}Rh: 100%).

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 ^{124}Xe gas target: ^{124}Xe(n, γ)^{125}Xe.

^{125}Xe decays into ^{125}I by electron-capture (EC) transition: $^{125}Xe \rightarrow {}^{125}I + \nu + E_b$.

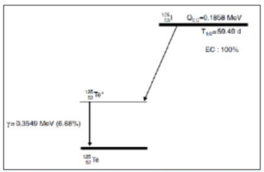
^{125}I decays by EC into an excited state ^{125}Te*, producing the maximum photon energy of 35.5 keV by gamma decay (6.7% of the time).

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

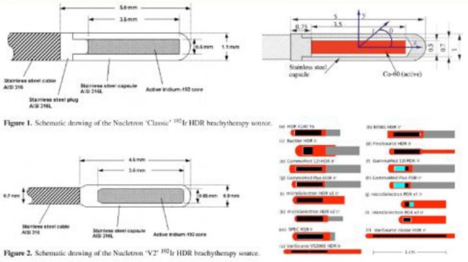


Figure 1. Schematic drawing of the Nucleton 'Classic' ^{192}Ir HDR brachytherapy source.

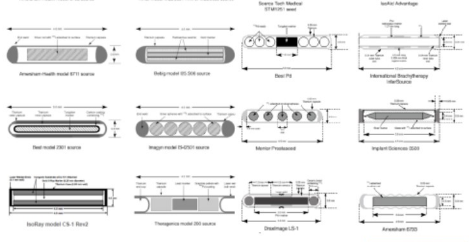
Figure 2. Schematic drawing of the Nucleton 'V2' ^{192}Ir HDR brachytherapy source.

TUFTS UNIVERSITY

Tufts Medical Center

Photon Source Characteristics

Low Dose Rate Brachytherapy Sources



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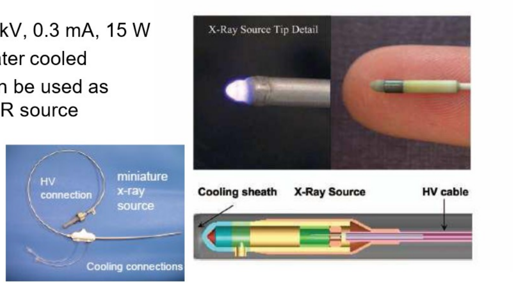
Photon Source Characteristics

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 [g 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

Photon Source Characteristics – Source Specification

Specification of gamma sources:

- Reference air kerma rate in air: $\left(\dot{K}_{air}(d_{ref})\right)_{air}$

  Defined by the ICRU reports 38 and 58 as the air kerma rate in air at the reference distance d_{ref} = 1m, corrected for the air attenuation and scattering [μGy / h]

- Air kerma strength: $S_k = \left(\dot{K}_{air}(d_{ref})\right)_{air} \times d_{ref}^2$

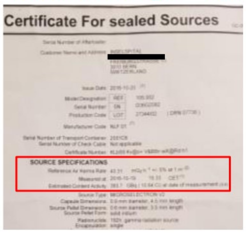
  In the AAPM TG43 recommendations: 1 U = 1cGy * cm^2 *h^{-1}

- Air kerma rate in air: $\left(\dot{K}_{air}(d)\right)_{air} = \frac{A_{app}\Gamma_{AKR}}{d^2}$

  A_{app}: apparent activity [Bq]
  Γ_{AKR}: air kerma rate constant [μGy*m^2 / (GBq*h)]
  d: distance [m]

KERMA: Kinetic Energy Released per unit of Mass. Mean energy transferred from indirect ionizing radiation (photons) to charged particles (electron).

Source Strength – Certificate

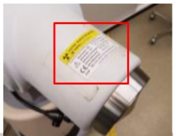


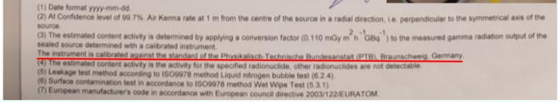
Certificate For sealed Sources

[redacted]

SOURCE SPECIFICATIONS

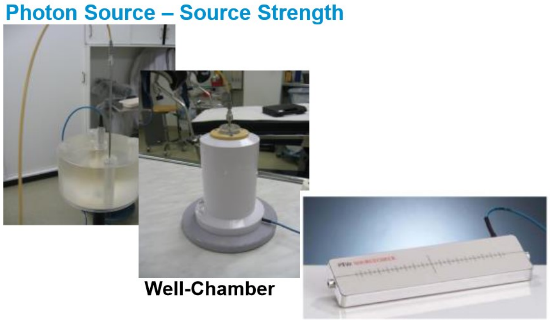
All international recommendations indicate the convention of specifying the sources exclusively in units of reference air kerma rate traceable to Accredited Calibration Laboratory.





(1) Date format yyyy-mm-dd.
(2) At Confidence level of 99.7%. Air Kerma rate at 1 m from the centre of the source in a radial direction, i.e. perpendicular to the symmetrical axis of the source.
(3) The estimated content activity is determined by applying a conversion factor (0.110 mGy m^2 h^{-1} GBq^{-1}) to the measured gamma radiation output of the sealed source determined with a calibrated instrument.
The instrument is calibrated against the standard of the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany.
(4) The estimated content activity is the activity for the specified radionuclide, other radionuclides are not detectable.
(5) Leakage test method according to ISO9978 method Liquid nitrogen bubble test (6.2.4).
(6) Surface contamination test in accordance to ISO9978 method Wet Wipe Test (5.3.1).
(7) European manufacturer's code in accordance with European council directive 2003/122/EURATOM.

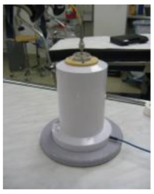
Photon Source – Source Strength



Well-Chamber

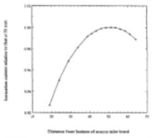
Figure 2: SourceCheck source strength device

Source Strength – Well Chamber



Well chamber and electrometer having calibrations traceable to an Accredited Calibration Laboratory (within 2 years as indicated by the dates on the form)

The electrometer needs to be calibrated in both current and charge (integral) modes.



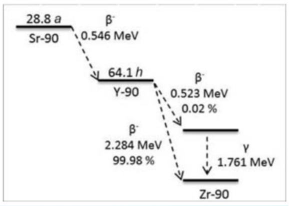
Goetsch et al., Phys. Med., 18(3) ,1991

The source is programmed to go to a series of positions within the well chamber and the maximum current reading is used to calculate the activity in air kerma units.

Consistency check every 3 months (with a Cs137 Source)

Beta sources – ^{90}Sr/^{90}Y

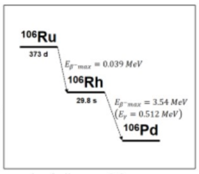
- Byproduct of nuclear fission
- Therapeutic radiation is primarily from 2.27 MeV betas from Y-90
- Suitable for treatment of superficial lesions, ocular lesions and coronary vessels
- Limited depth of penetration



Beta sources – ^{106}Ru

Ruthenium-106 (^{106}Ru) is a pure β^- emitter with a half-life of ~373 days.

It decays to the ground state of rhodium-106 (^{106}Rh). The half-life of ^{106}Rh is only ~29.8 seconds



Rhodium-106 is also a pure β^- emitter. Its decay is followed by emission of gamma-rays from de-excitations of its daughter-nucleus ^{106}Pd.

^{106}Ru is commercially obtained from neutron irradiated high enrichment ^{235}U target in process of production ^{99}Mo. After isolation of ^{99}Mo radioisotope and decaying of ^{103}Ru, ruthenium is separated from the wastes by multistep procedure.

Brachytherapy – 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 whole lifetime of the sources
- The sources undergo complete radioactive decay
- In general, the sources are not removed from the patient after complete decay

Brachytherapy – Type of implants

Intracavitary

- GYN, rectum

Interstitial

- HNO, lip, eyelid, mamma, rectum, prostate

Surface plaque

- Skin surface or eye cornea

Intraluminal

- Bronchus, oesophagus, HNO

Intraoperative

- Single catheter or flabs for sarcomas, gynecologic and rectal cancer recurrences

Intravascular

- Peripheral vascular diseases (vessels narrowing)

Brachytherapy – 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

Brachytherapy – Source loading

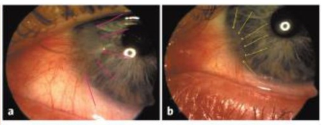
- Hot loading
  The applicator is pre-loaded and contains radioactive sources at time of placement into the patient

- Afterloading
  The applicator is placed first into the patient and the radioactive sources are loader later:
  - Manual afterloading
  - Automatic remote afterloading

Source loading – Hot loading

- Pterygium is a benign conjunctival neoformation. Standard treatment is a surgical excision followed by adjuvant beta irradiation.
- $^{90}Sr/^{90}Y$ eye applicators are used for treatment of pterygium.

Figure 1. Strontrium-/yttrium-90 applicator.

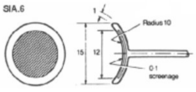


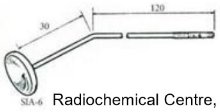
Figures 3a and 3b. A patient's eye prior to (a) and after treatment (b) at 6-month follow-up.

I. Vastardis et al., Strahlenther Onkol 185, 808–14. 2009

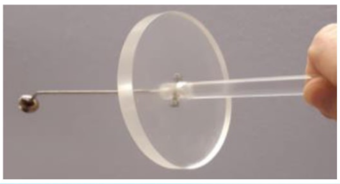
Source loading – Hot loading

Curved $^{90}Sr/^{90}Y$ eye applicator (SIA.6) used for treatment of pterygium.





Radiochemical Centre, Amersham, UK

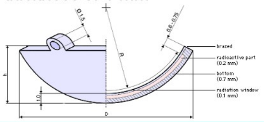


Source loading – Hot loading

Intraocular melanoma is the most malignant eye tumor, which can be treated with eye plaques either:

- loaded with radioactive ^{125}I seeds

- or where a thin film of ^{106}Ru is encapsulated within a sheet of pure silver (Ag 99.99), with a total thickness of 1 mm



From: eyephysics.com

Source loading – Afterloading

Manual Afterloader: Radiation sources are manually afterloaded into applicators or catheters that have been places within the target volume:

- Manual loading and removal of the sources from the applicators or catheters result in some radiation exposure of the medical and support staff

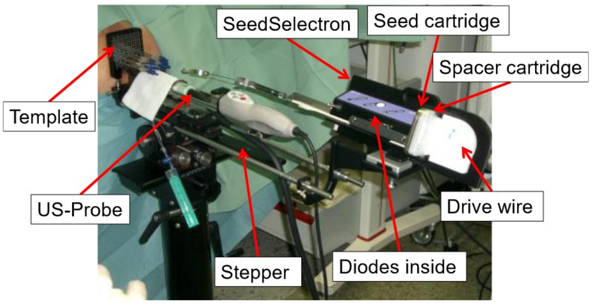
Source loading – Afterloading

Remote Afterloader: Computer driven afterloading systems:

- Reduction of the radiation exposure to medical and support staff
- Increase patient throughput
- Consistent and reproducible treatment delivery

Source loading – LDR Afterloading Systems

Permanent Prostate Implant with ^{125}I seeds



Source loading – HDR Afterloading Systems

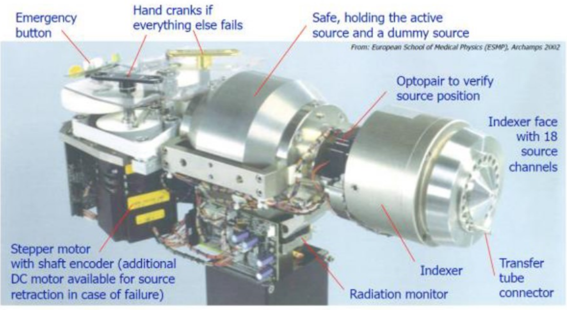

Flexitron (Elekta)


MultiSource
(Eckert & Ziegler BEBIG)

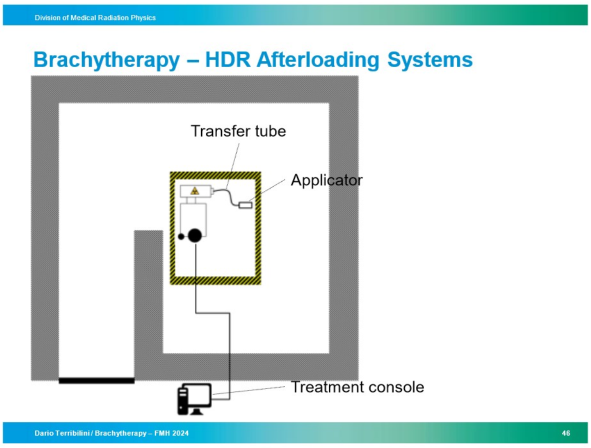

microSelectron (Elekta)


GammaMed (Varian)

Source loading – HDR Afterloading Systems



From: European School of Medical Physics (ESMP), Archamps 2002



Division of Medical Radiation Physics

Brachytherapy – HDR Afterloading Systems

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Brachytherapy – HDR Afterloading Systems

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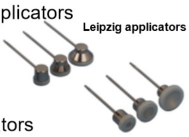
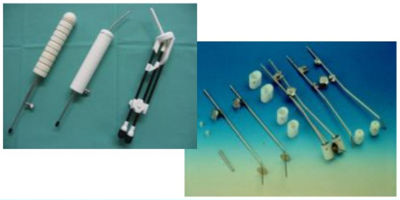
Brachytherapy – Applicators

Surface applicators



Leipzig applicators

Gynecological applicators



Brachytherapy – Applicators

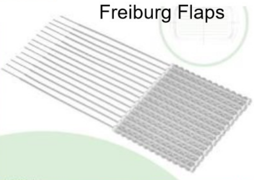
Needles

Catheters

Breast applicators

https://openi.nlm.nih.gov/

Freiburg Flaps



Dosimetry Systems

Dosimetry Systems

Dosimetric systems are set of rules, specific to a radioisotope and its spatial distribution in the applicator to deliver a defined dose to a designated region

Within any system, specification of treatment in terms of dose, timing, and administration is necessary so as to implement prescription in a reproducible manner

---

Historical Dosimetry Systems – Uterine Cervix

Stockholm

- Radium
- 2-3 applications within about a month
- Intravaginal boxes made up of silver or lead
  - 60-80 mg of Radium
- Intrauterine tube made up of rubber
  - 30-90 mg of Radium
- 20-30 hours per session

➔Total dose 6500 - 7100 mg hrs

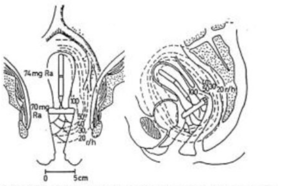


Figure 3.1. The Stockholm system. Typical treatment of a cervix carcinoma with a radium application (uterus normal in size and shape). The total amount of radium is 74 mg + 70 mg = 144 mg of radium. The exposure rates (roentgen per hour) are shown in the frontal and sagittal plane. An amount of 144 mg of radium (1 mm Pt filtration) delivers a total reference air-kerma rate of 964 μGy h^{-1}. After 3 applications of 27 h each, the TRAK would be 78 mGy and a source mass × duration of 11,664 mg h (Walstam, 1954) (from ICRU 1985). The relationship between exposure, absorbed dose, and air kerma is described in Section 11.

ICRU 89 (2013): Prescribing, Recording, and Reporting Brachytherapy for Cancer of the Cervix

---

Historical Dosimetry Systems – Uterine Cervix

Paris

- Radium
- Single application
- 2 cork colpostats in the vagina
  - 13.3 mg of Radium each
- Intrauterine tube made of thin rubber with 3 radioactive sources
  - 33.3 mg
  - source strengths distribution: 1:1:0.5
- 120 hours

➔Total dose of 7000-8000 mg hrs

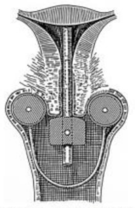


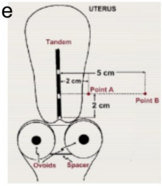
Figure 3.2. Schematic representation of the "historical" Paris method. Assuming three intra-uterine sources of 10 mg radium each and 3 intra-vaginal sources of 10 mg each, the total activity of 60 mg (1 mm Pt filtration) would deliver a TRAK rate of 402 μGy h^{-1}. After an application of 6 days (144 h), the TRAK would be 57.9 mGy and a source-mass × duration of 8,640 mg h (ICRU, 1985; Pierquin 1964).

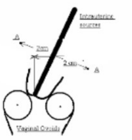
ICRU 89 (2013): Prescribing, Recording, and Reporting Brachytherapy for Cancer of the Cervix

Historical Dosimetry Systems – Uterine Cervix

Manchester system is characterized by the dose to following points:

- Point A: Dose prescription point. Define the duration of the irradiation
- Point B: Describe the dose fall off outside the target. It gives the dose in the vicinity of the pelvic wall near the obturator nodes.
- Bladder point
- Rectum point





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

Historical Dosimetry Systems – Uterine Cervix

Manchester

- Radium
- Standard applicators
  - Pair of ovoids: 40% of the dose to point A
  - Intrauterine tube: 60% of the dose to point A
- Total dose at point A: 8000 mg hrs
- 2 sessions

➔Total irradiation time: 144 hours

Historical Dosimetry Systems

Because of the inherent radiation safety risk, ^{226}Ra has been progressively abandoned and is forbidden in some countries and by several authorities.

It has been replaced by artificial radionuclides, such as ^{60}Co, ^{137}Cs, and ^{192}Ir.

The lower energy of the gamma emissions of ^{137}Cs and ^{192}Ir also simplifies the practical problems of room shielding and reduces the exposure to staff.

Historical Dosimetry Systems

The replacement of radium by ^{137}Cs, ^{192}Ir and ^{60}Co followed one of two options:

- The new sources (^{137}Cs or ^{60}Co) were similar in size and shape and had an output similar to radium sources. The same technique of application could then be used, and the clinical experience gained with radium remained fully relevant.
- Using ^{192}Ir takes advantage of improved technology in the preparation of the sources:
  - increased specific activities
  - miniaturized sources

Dosimetry Systems – ICRU 38 (GYN)

For a reliable comparison of the different methods and their results ICRU 38 recommends a common terminology for prescribing recording and reporting of intracavitary brachytherapy applications.

ICRU 38 recommend a system of dose specification that relates to a dose distribution to the target volume instead of the dose to a point.

➔ Instead of prescribing the dose to a point, the dimensions of the volume included in the **reference dose level of 60 Gy**.

The 60 Gy reference volume may be equal to or different from the treated volume. The treated volume should encompass at least the clinical target volume (CTV).

The reference dose level of 60 Gy is for LDR. For HDR a reference dose lower than 60 Gy is recommended

When intracavitary therapy is combined with external beam therapy, the dose level to define the reference volume is the difference between 60 Gy and the dose delivered by external beam therapy.

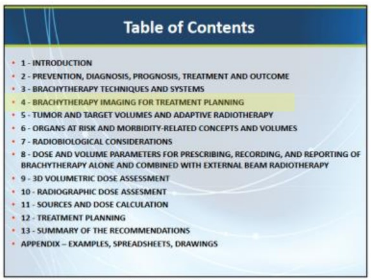
Dosimetry Systems – ICRU 38 (GYN)

- Description of the technique
  - Applicator type
  - Source type, strength and arrangement
  - Loading technique
- Total reference air kerma
- Description of the reference volume
  - Dimensions: Heigth (d_h), width (d_w) and thickness (d_t) of the pear shaped isodose
- Absorbed dose at reference points
  - Point A
  - Point B
  - Bladder point
  - Rectum point
  - Lymphatic Trapezoid of Fletcher
  - Pelvic Wall points
- Time dose pattern
  - Dose rate and duration

Dosimetry Systems – 2D ➔3D

ICRU 38 mainly provide recommendations for applications planned on the basis of radiographs.

➔ICRU 89 (GYN)



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- 5 - TUMOR AND TARGET VOLUMES AND ADAPTIVE RADIOTHERAPY
- 6 - ORGANS AT RISK AND MORBIDITY-RELATED CONCEPTS AND VOLUMES
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- 9 - 3D VOLUMETRIC DOSE ASSESSMENT
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- 11 - SOURCES AND DOSE CALCULATION
- 12 - TREATMENT PLANNING
- 13 - SUMMARY OF THE RECOMMENDATIONS
- APPENDIX – EXAMPLES, SPREADSHEETS, DRAWINGS

BrachyNext – Working Together to Shape the Future of Brachytherapy

ICRU 89 (GYN)

Use imaging (US, CT, MRI, PET) to:

- conform the dose to the target
- Effectively spares OARs

MRI:

- Superior soft tissue resolution
- HRCTV smaller than on CT
- Greater conformality will lead to decrease dose to OARs
  - Possibly more critical for large lesions
- First fraction or every fraction
  - Beware of significant tumor response
  - $T_{1/2}$ for tumor response 20-21 days (CT, MR, clinical exam)

Historical Dosimetry Systems – Intertitial

The most commonly used systems in interstitial Brachytherapy were:

- Patterson-Parker (Manchester) system
- Paris system
- Quimby (Memorial) system

Historical Dosimetry Systems – Intertitial

Manchester (Patterson-Parker) System

The radioactive sources are distributed non-uniformly over the area or the volume of the implant to give a uniform dose distribution. The aim of the system is to deliver a uniform dose of ± 10 % in the implanted area or volume.

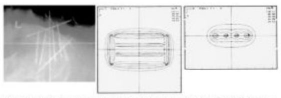


Fig 6.2: Manchester System for application of radioactive sources with different loading. Fig A shows the localisation film. Fig B and C give the distribution of dose rate for a single-plane implant with iridium wires of unequal linear activity in order to ensure dose uniformity throughout the implanted 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])

Patterson-Parker tables

Single plane

This source arrangement treats a 1cm thick slab of tissue. The prescribed dose is on a parallel plane 0.5cm away from the source plane

Double plane

It is used to treat slabs with thickness between 1cm and 2.5cm. The required total source strength is equally divided between the two planes

---

Historical Dosimetry Systems – Intertitial

Paris System

Paris system was developed for linear sources of iridium wires. It is used for single or double plane implants. In this system, sources are distributed uniformly for a planar implant but follow a particular pattern for volume implants:

- 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
- Adjacient sources must be equidistant to each other

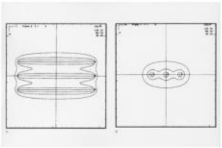
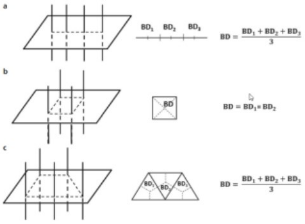


Fig 6.3 : Iridium-192 wire implant according to the Paris system (single-plane implant). The wires are of equal linear activity, parallel, and arranged in such a way that their centres are in the same plane perpendicular to the direction of the wires (i.e. the central plane, see Fig 6.4). (From Wambersie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

Historical Dosimetry Systems – Intertitial

Paris System

The Paris system recommends as a guideline for the reference dose rate (i.e. the dose rate with which the irradiation time is determined) 85% of the basal dose rate.



From: Dutreix A, Marinello G, Wambersie A (1982) Dosimetrie en Curietherapie

Historical Dosimetry Systems – Intertitial

Quimby (Memorial) System

The radioactive sources are distributed uniformly over a plane or a volume of tissue. The dose near the center of the implant is much greater than at the edge of the implant. Thus in Quimby system, a uniform distribution of radioactive sources is used to give a non-uniform dose distribution.

Dosimetry Systems/Planning – Afterloading

The target volume is covered with a sufficient radiation dose by introducing a sufficient number of spatially suitably distributed source positions into the tissue. The planning and preparation of the irradiation takes place in 3 steps:

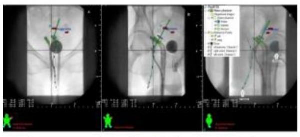
1. Determination of a suitable application geometry to enable a suitable distribution of the source positions and insertion of the applicators.
2. Reconstruction of the application geometry based on CT, MR, radiography or ultrasound images.
3. Optimization: Determination of the source positions and dwell times. Steps 2 and 3 are usually carried out with computer-aided treatment planning systems.

Dosimetry Systems/Planning – Reconstruction

Source/implant/applicator localization:

2D

- ➢ Projections



3D

- ➢ Computerized tomography (CT) scanning
- ➢ Ultrasound scanning (US)
- ➢ Magnetic resonance imaging (MRI)

Dosimetry Systems/Planning – Optimization

Geometrical optimization

The goal of the geometric optimization is to reduce the inhomogeneity in a given distribution of the source positions by adjusting the dwell times at given source strengths :

- Distance Optimization
- Volume Optimization
- …

Anatomy based optimization

The aim of the anatomy based optimization is to meet the target requirements set by the planner on given structures of the anatomy by modulating the dwell times of the source positions or by specifying seed locations at given source strengths:

- HIPO
- IPSA
- Manual, …

Dosimetry Systems – ICRU 58

The aim of the ICRU 58 was to develop a common language that was based on the presently existing concepts.

The ICRU 58 was written to generate a guideline about the dose specification and reporting for interstitial brachytherapy.

Dosimetry Systems – ICRU 58 reporting

- Description of the clinical target volume
- Sources
- Source strength
  - Reference air kerma rate in air [cGy/h @ 1m]
- Technique and implant time
- Prescription dose
- Description of the dose distribution
  - Total reference air kerma
  - Mean central dose
  - Minimum dose
  - High dose regions
  - Dose uniformity indices
- Dose volume histograms (DVH)

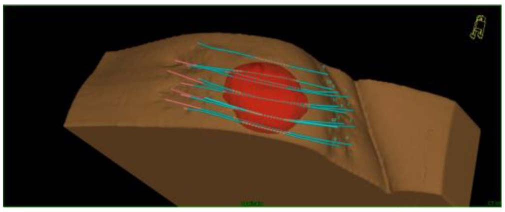
Brachytherapy – Mamma Ca

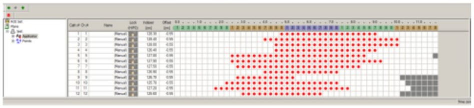
Mamma Ca: Interstitial brachytherapy, partial breast radiation

Planning – CT acquisition

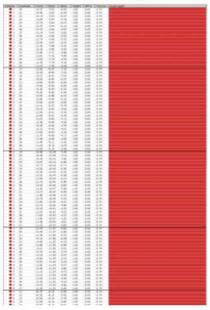
Planning – Contouring

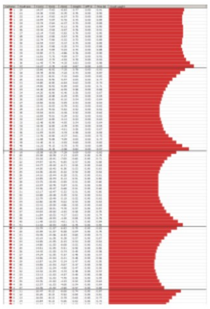
HDR Planning - Activation



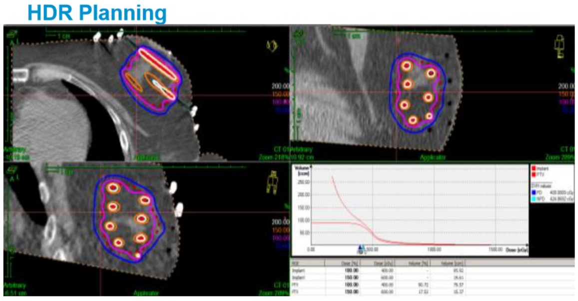


HDR Planning - Optimization

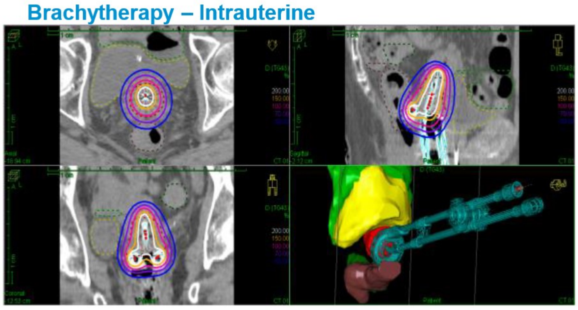




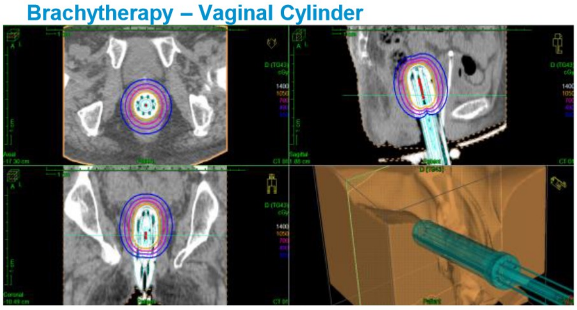
HDR Planning



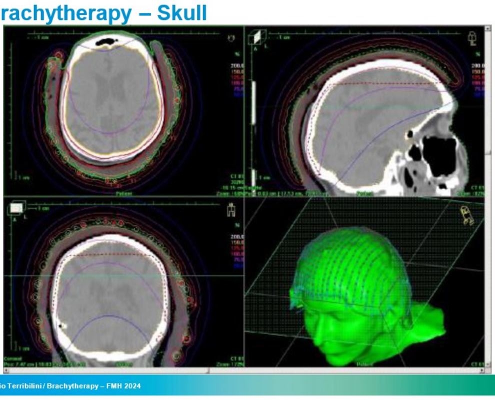
Brachytherapy – Intrauterine

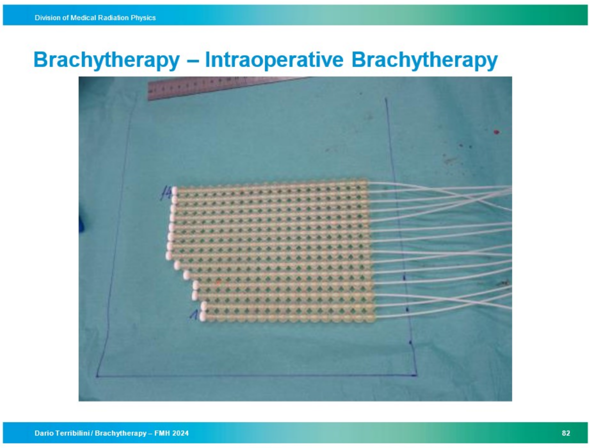


Brachytherapy – Vaginal Cylinder



Brachytherapy – Skull



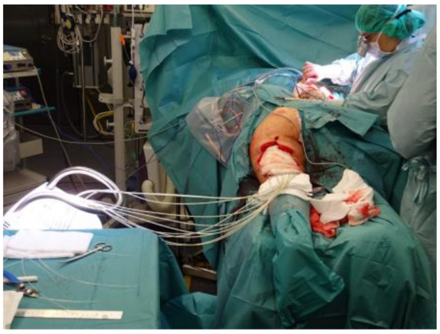


Brachytherapy – Intraoperative Brachytherapy

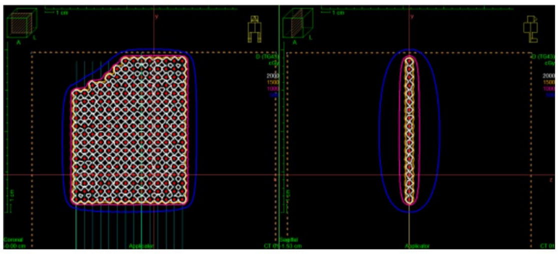
Brachytherapy – Intraoperative Brachytherapy

Brachytherapy – Intraoperative Brachytherapy

Brachytherapy – Intraoperative Brachytherapy



Brachytherapy – Intraoperative Brachytherapy



Brachytherapy – Intraoperative Brachytherapy

At the Inselspital IORTs are carried out for:

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

Prescription dose: 10 Gy @ 5mm tissue depth

Dose Calculation

- Point Source approximation
- TG43
- ACE (Collapsed Cone)
- Full Monte Carlo
- Acuros (Boltzmann Solver)

Dose Calculation

- Point Source approximation
- AAPM-TG43
- ACE (Collapsed Cone)
- Full Monte Carlo
- Acuros (Bolzmann Solver)

Today – Point Source

$$\dot{D}_{water}(r) = \dot{K}_{air}(r_{ref})_{air} \bullet \left[\frac{\bar{\mu}_{tr}}{\rho}\right]_{Air}^{Water} \bullet (1-g) \bullet T(r) \bullet \left(\frac{r_{ref}^{\ 2}}{r^2}\right)$$

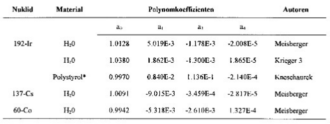
where:

$\left[\frac{\bar{\mu}_{en}}{\rho}\right]_{Air}^{Water}$: ratio of the photon mass energy absorption coefficients (water to air).

T(r) : Tissue attenuation and scatter function :

$$T(d) = \dot{K}_{air}(d)_{water} / \dot{K}_{air}(d)_{air} = a_0 + a_1 \bullet r + a_2 \bullet r^2 + a_3 \bullet r^3$$

Meisberger L.L., Keller R.J. and Shalek R.J.: "*The effective attenuation of the gamma rays of gold-198, Iridium-192, Caesium-137, Radium-226 and Cobalt-60*". Radiology 90, 953-957, 1968.



Nuklid	Material	Polynomkoeffizienten				Autoren
		a_0	a_1	a_3	a_4	
192-Ir	H_20	1.0128	5.019E-3	-1.178E-3	-2.008E-5	Meisberger
	H_20	1.0380	1.862E-3	-1.300E-3	1.865E-5	Krieger 3
	Polystyrol*	0.9970	0.840E-2	1.136E-1	-2.140E-4	Kneschaurek
137-Cs	H_20	1.0091	-9.015E-3	-3.459E-4	-2.817E-5	Meisberger
60-Co	H_20	0.9942	-5.318E-3	-2.610E-3	1.327E-4	Meisberger

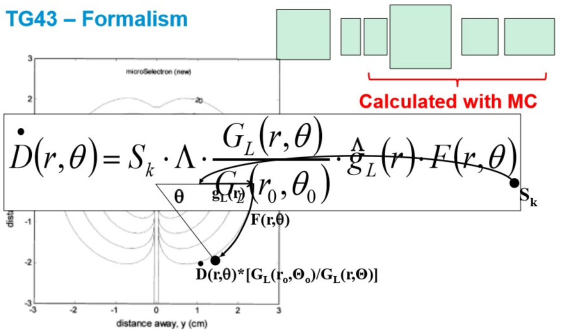
Polynomkoeffizienten für die radialen Tiefendosiskurven von Afterloadingstrahlern im Phantom (nach Gl. 6.16, *: zusätzliches Exponentialglied $e^{-\mu \cdot r}$ mit $\mu = 0.113\ cm^{-1}$).

From: Krieger, «Strahlenphysik, Dosimetrie und Strahlenschutz», Band 2, B.G.Teubner Stuttgard 1997

Dose Calculation

- Point Source approximation
- AAPM-TG43
- ACE (Collapsed Cone)
- Full Monte Carlo
- Acuros (Boltzmann Solver)

TG43 – Formalism



Calculated with MC

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

TG43 – Formalism

Kerma Strength: $S_k = \dot{K}_\delta(b) \cdot b^2$ Measured for each source <u>individually</u>.

Dose Rate Constant: $\Lambda = \frac{\dot{D}(r_0,\theta_0)}{S_k}$ Measured or calculated with Monte Carlo for each source model.

Radial Dose Function: $g_L(r) = \frac{\dot{D}(r,\theta_o)}{\dot{D}(r_o,\theta_o)} \cdot \frac{G_L(r_o,\theta_o)}{G_L(r,\theta_o)}$

Anisotropy Function: $F(r,\theta) = \frac{\dot{D}(r,\theta)}{\dot{D}(r,\theta_o)} \cdot \frac{G_L(r,\theta_o)}{G_L(r,\theta)}$

Calculated with Monte Carlo for each source model.

with:
r_o = 1cm
Θ_o = 90°

TG43 – …some numbers for our Ir-192 Source

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

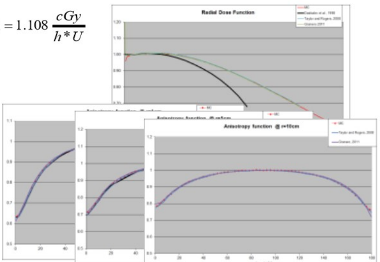
$1U = 1 \frac{\mu Gy \bullet m^2}{h}$

(Typical value after source replacement)

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

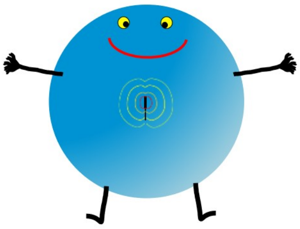
Radial Dose Function:

Anisotropy Function:



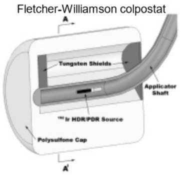
TG43 – Basic assumptions (…and limitations)

- 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



TG43 – Shieldings & Applicators

Fletcher-Williamson colpostat



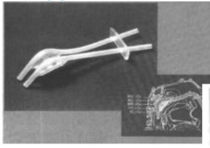


Figure 5. HDR tandem and cylinder applicator.

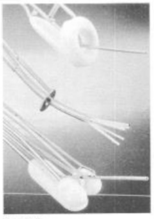
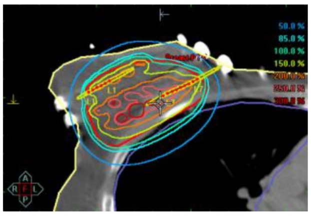


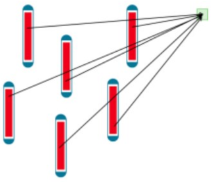
Figure 18.27
From top to bottom: Ring applicator, Bauer endometrial, and Joslin-Flynn Cervix applicator. (Reprinted with permission, Nucletron-Oldelft Corporation, Columbia, MD.)

TG43 – Limitations

Patient Size Effect

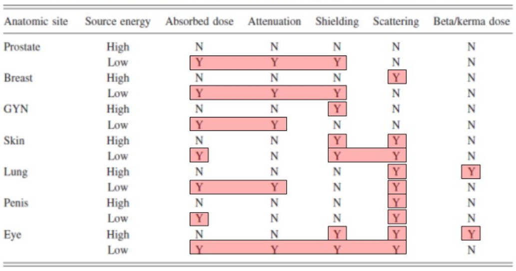


Interseed effects



TG43 – 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.

TG43 – Basic assumptions (…and limitations)

- Dose calculation in water
  - no material heterogeneities within the
  - no applicators
  - no shieldings
  - no source inte
- In
  - size effect
- Azimuthal symmetry

But very fast and in most cases accurate enough

Alternative Approaches

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

into account which are ignored by the TG43 protocol

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

AAPM TG 186

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

Åsa Carlsson Tedgren

Jean-François Carrier

Stephen D. Davis

Firas Mourtada

Mark J. Rivard

Rowan M. Thomson

Frank Verhaegen

Todd A. Wareing

Jeffrey F. Williamson

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

Main issues covered by the A
- Limitations of the AAPM T
- Review model-based bracl algorithms
- Dose report ($D_{m,m}$, $D_{w,m}$, D
- CT imaging and patient mo
  - Media definition
  - Applicators, sources and oth
- MBDCA Commissioning
  - Level 1: MBDCA should fall conditions (same as TG-43)
  - Level 2: MBDCA should tak and scatter conditions

AAPM TG 186 – Dose Report

$D_{w,m}$ or $D_{m,m}$

Medium of dose specification

Medium of radiation transport

As available evidence does not directly support $D_{w,m}$, reporting $D_{m,m}$ is preferred as it is a conceptually well-defined quantity, in contrast to $D_{w,m}$, which is a theoretical construct without a physical realization in a nonwater medium. On the basis of all these considerations, it is the consensus of TG-186 to require only reporting of $D_{m,m}$ when using MBDCAs. This does not preclude individual practitioners or protocol groups from reporting $D_{w,m}$ or other quantities of interest along with $D_{m,m}$.

AAPM TG 186 – CT imaging and Patient modelling

- Consensus material definition

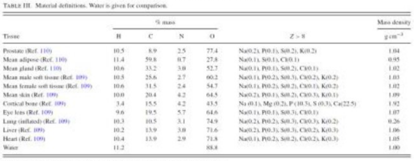


TABLE III. Material definitions. Water is given for comparison.

Tissue	% mass H	C	N	O	Z > 8	Mass density g cm^{-3}
Prostate (Ref. 110)	10.5	8.9	2.5	77.4	Na(0.2), P(0.1), S(0.2), K(0.2)	1.04
Mean adipose (Ref. 110)	11.4	59.8	0.7	27.8	Na(0.1), S(0.1), Cl(0.1)	0.95
Mean gland (Ref. 110)	10.6	33.2	3.0	52.7	Na(0.1), P(0.1), S(0.2), Cl(0.1)	1.02
Mean male soft tissue (Ref. 109)	10.5	25.6	2.7	60.2	Na(0.1), P(0.2), S(0.3), Cl(0.2), K(0.2)	1.03
Mean female soft tissue (Ref. 109)	10.6	31.5	2.4	54.7	Na(0.1), P(0.2), S(0.2), Cl(0.1), K(0.2)	1.02
Mean skin (Ref. 109)	10.0	20.4	4.2	64.5	Na(0.2), P(0.1), S(0.2), Cl(0.3), K(0.1)	1.09
Cortical bone (Ref. 109)	3.4	15.5	4.2	43.5	Na (0.1), Mg (0.2), P (10.3), S (0.3), Ca(22.5)	1.92
Eye lens (Ref. 109)	9.6	19.5	5.7	64.6	Na(0.1), P(0.1), S(0.3), Cl(0.1)	1.07
Lung (inflated) (Ref. 109)	10.3	10.5	3.1	74.9	Na(0.2), P(0.2), S(0.3), Cl(0.3), K(0.2)	0.26
Liver (Ref. 109)	10.2	13.9	3.0	71.6	Na(0.2), P(0.3), S(0.3), Cl(0.2), K(0.3)	1.06
Heart (Ref. 109)	10.4	13.9	2.9	71.8	Na(0.1), P(0.2), S(0.2), Cl(0.2), K(0.3)	1.05
Water	11.2			88.8		1.00

Ref. 109: ICRU Report 46; Ref. 110: Woodard and White 1986

- Material assignment method

  For a given organ, it is recommended that the tissue composition assignment be guided by contours approved by the radiation oncologist.
- CT artifact removal

  If imaging artifacts are present, we recommend a complete override of the tissue in question with a uniform density, which may be the average of neighboring pixels.

Dose Calculation

- Point Source approximation
- AAPM-TG43
- ACE (Collapsed Cone)
- Full Monte Carlo
- Acuros (Boltzmann Solver)

Analytical Models - PSS Formalism

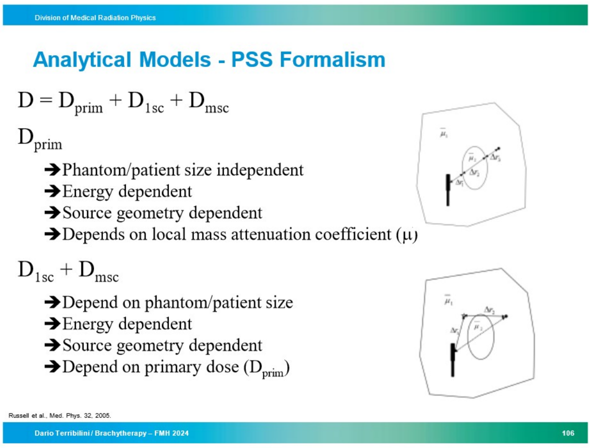
Dose is deposited locally through primary electrons set in motion by a photon interaction and a large fraction through scattered components.

➔ Separation of the primary dose and scattered dose components:

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

➔ New resampling of the TG43 data.

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



Analytical Models - PSS Formalism

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

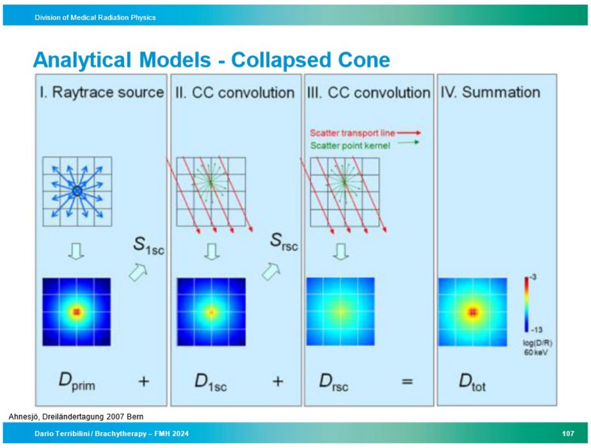
D_{prim}

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

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

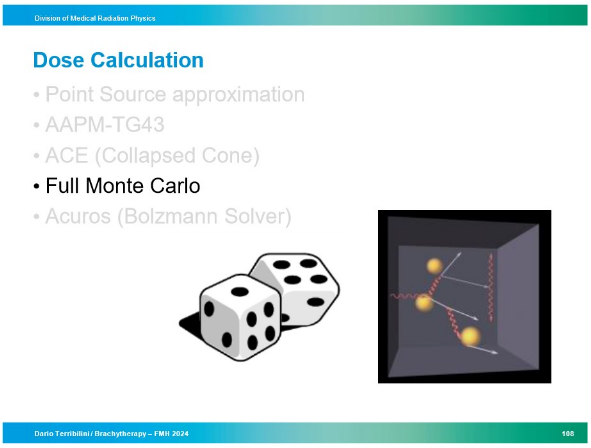
- ➔Depend on phantom/patient size
- ➔Energy dependent
- ➔Source geometry dependent
- ➔Depend on primary dose (D_{prim})

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



Analytical Models - Collapsed Cone

Ahnesjö, Dreiländertagung 2007 Bern

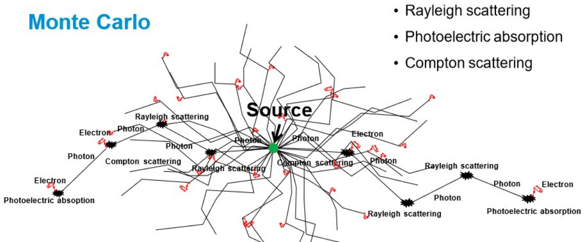


Dose Calculation

- Point Source approximation
- AAPM-TG43
- ACE (Collapsed Cone)
- Full Monte Carlo
- Acuros (Bolzmann Solver)

Monte Carlo

- Rayleigh scattering
- Photoelectric absorption
- Compton scattering



Dose per simulated history ~10^{-13} 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.

Monte Carlo – Drawbacks in Brachytherapy

- Due to the $1/r^2$ behaviour of the primary dose component in brachytherapy, statistics rapidly degrade with increasing distance from the sources.
- Photons travel relatively long distances before interacting and their transport steps are often interrupted by boundary crossings.
- Elastic scattering does not deposit energy but still needs to be simulated.
  Dose deposition needs many interaction steps.

Monte Carlo – Dose Deposition

Dose is deposited through electrons released by photon interactions. Due to the low energies in brachytherapy, the electron range is short. Thus, dose can be approximated as kerma (kinetic energy released per mass):

➔ Dose ~ Kerma

$$D \overset{CPE}{=} \left(\frac{\mu_{en}}{\rho}\right)_m \Psi = K_{collision}$$

➔ No electron transport

Dose Calculation

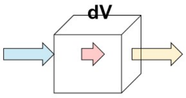
- Point Source approximation
- AAPM-TG43
- ACE (Collapsed Cone)
- Full Monte Carlo
- Acuros (Boltzmann Solver)

Tomorrow – Boltzmann Solver

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

$$\hat{\Omega}\cdot\vec{\nabla}\Psi(\vec{r},E,\hat{\Omega}) + \sigma_t(\vec{r},E)\Psi(\vec{r},E,\hat{\Omega}) = Q^{\text{scat}}(\vec{r},E,\hat{\Omega}) + Q^{\text{ex}}(\vec{r},E,\hat{\Omega})$$

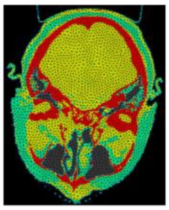
Streaming operator	Collision operator	Scattering source	External source
$\hat{\Omega}\cdot\vec{\nabla}\Psi(\vec{r},E,\hat{\Omega})$	$\sigma_t(\vec{r},E)\Psi(\vec{r},E,\hat{\Omega})$	$Q^{\text{scat}}(\vec{r},E,\hat{\Omega})$	$Q^{\text{ex}}(\vec{r},E,\hat{\Omega})$
Number of particles flowing into a volume 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.

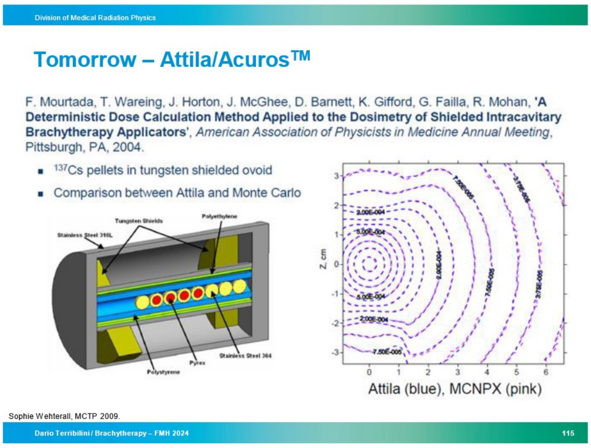
Tomorrow – Boltzmann Solver



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).



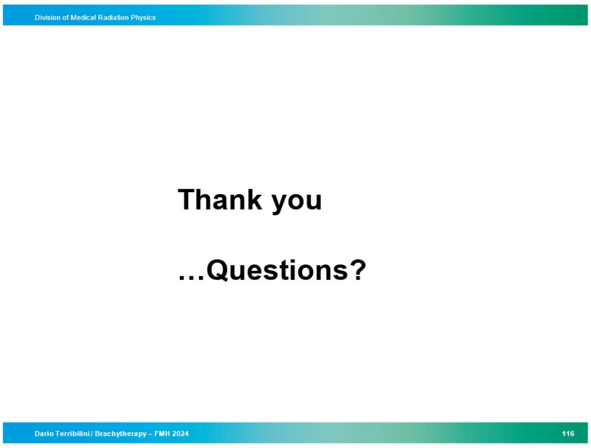
Tomorrow – Attila/Acuros™

F. Mourtada, T. Wareing, J. Horton, J. McGhee, D. Barnett, K. Gifford, G. Failla, R. Mohan, **'A Deterministic Dose Calculation Method Applied to the Dosimetry of Shielded Intracavitary Brachytherapy Applicators'**, *American Association of Physicists in Medicine Annual Meeting*, Pittsburgh, PA, 2004.

- ^{137}Cs pellets in tungsten shielded ovoid
- Comparison between Attila and Monte Carlo

Attila (blue), MCNPX (pink)

Sophie Wehterall, MCTP 2009.



Thank you

…Questions?