MIRD formalism: theory and examples

KU LEUVEN

Prof.dr. Patrick Dupont
Nuclear medicine
KU Leuven – UZ Leuven
Belgium

Contents

KU LEUVEN

- Basic definitions
  - Radiation dose
  - Equivalent dose
  - Source and target organs
- MIRD formalism
  - Cumulated activity
  - Residence time
  - Equilibrium absorbed dose constant
  - Absorbed fraction
  - S-values
  - Phantoms
- Application 1: Radiation dose estimates for tracers used in nuclear medicine
- Application 2: Patient specific dosimetry in radio-immuno therapy (RIT)

Radiation dose

KU LEUVEN

- Radiation dose D = the quantity of radiation energy deposited in an absorber per kg of absorber material.
- SI unit: Gy

  1 Gy = 1 J energy deposited per kg absorber
- Old unit: rad

  1 rad = 1 cGy

Equivalent dose

KU LEUVEN

Equivalent dose H = absorbed dose D x Q

Q is the radiation weighting factor for a specified type and energy of radiation accounts for the effectiveness of the radiation in causing biological damage.

Unit: Sievert (Sv)

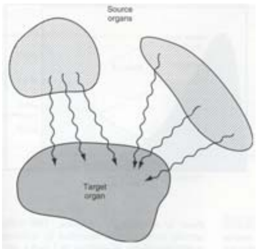
Old unit:
1 rem = 10 mSv

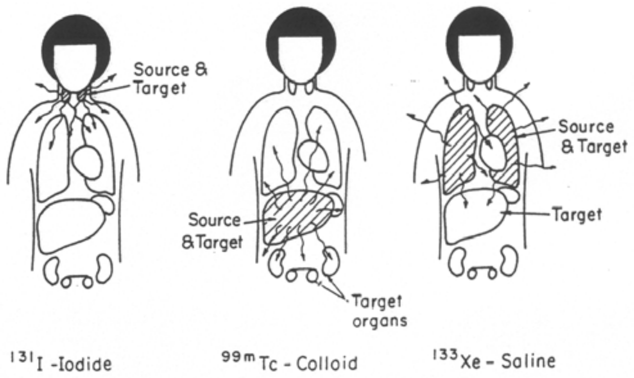
Type of radiation	Weighting factor Q
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons, energy	
<10 keV	5
10 - 100 keV	10
100keV - 2 MeV	20
2 - 20 MeV	10
>20MeV	5
Protons, energy > 2 MeV	5
Alpha particles	20

KU LEUVEN

Source and target organs

– Source organs (i.e. organs with significant uptake of isotope)
– Target organs (i.e. organs that are receiving radiation)





KU LEUVEN

MIRD (Medical Internal Radiation Dose)

1. The amount of activity and time in source and target organs
2. Total amount of radiation energy emitted by the radioactivity
3. Fraction of energy emitted by the source organ that is observed by the target organ

KU LEUVEN

MIRD method

1. The amount of activity and time in source and target organs
2. Total amount of radiation energy emitted by the radioactivity
3. Fraction of energy emitted by the source organ that is observed by the target organ

KU LEUVEN

MIRD method

1. The amount of activity and time in source and target organs
2. Total amount of radiation energy emitted by the radioactivity
3. Fraction of energy emitted by the source organ that is observed by the target organ

KU LEUVEN

The amount of activity and time in source and target organs

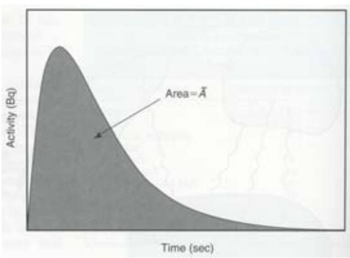
- Activity in an organ is continuously changing due to various factors:
  - uptake of the radiopharmaceutical
  - excretion from the organ
  - physical decay
- Time activity curves (TAC)
  physical and biological properties
- A(t) activity in organ at time t.

KU LEUVEN

The amount of activity and time in source and target organs

- Cumulated activity Ã
- SI unit: Bq.s
  - Activity administered to the patient at t=0
  - Measurement until complete disappearance from the organ ($t \rightarrow \infty$).
- Residence time τ

$$\tilde{A} = \int_0^\infty A(t)\,dt$$



$$\tau = \tilde{A} / A_{injected}$$

KU LEUVEN

Calculation of Ã

- Situation 1: uptake by the organ is instantaneous (= very rapid with respect to the half-life of the radionuclide) and there is no biological excretion

  $A(t) = A(0).\exp(-\ln(2).t/t_{1/2})$

  $\tilde{A} = t_{1/2}.A(0)/\ln(2)$

- Example: cumulated activity in the liver for an injection of 100 MBq of a ^{99m}Tc-labeled sulfur colloid assuming that 60% of the injected colloid is trapped by the liver (and retained there)

  $\tilde{A} = 6.02hr \times (0.6 \times 100MBq)/\ln(2) = 521\ MBq.hr = 1.88 \times 10^{12}\ Bq.s$

  $\tau = 5.21\ hr$

KU LEUVEN

Calculation of Ã

- Situation 2: Uptake is instantaneous and clearance is by both physical decay and biological excretion. Biological half-life = T_b.

  Total clearance is described by

  $$\frac{1}{T_e} = \frac{1}{T_b} + \frac{1}{T_{1/2}}$$

  $$T_e = \frac{T_b T_{1/2}}{T_b + T_{1/2}}$$

  $\tilde{A} = T_e.A(0)/\ln(2)$

- If there is more than one component to the biological excretion curve, then each component i (with fraction f_i) has a biological half-life of T_{b_i} and an effective half-live T_{e_i}

$\tilde{A} = [f_1.T_{e_1} + f_2.T_{e_2} + \ldots].A(0)/\ln(2)$

Calculation of Ã

KU LEUVEN

- <u>Example</u>: 100 MBq of ^{99m}Tc-labeled microspheres are injected into a patient, with essentially instantaneous uptake of activity in the lungs. Suppose that because of a metabolic defect 60% of the activity is excreted from the lungs with a half-life of 2 hours and 40% with a half-life of 3 hours. The cumulated activity in the lungs is given by:

$\tilde{A} = [0.6\ T_{e_1} + 0.4\ T_{e_2}]100\text{MBq}/\ln(2)$

with $T_{e_1} = 6.02 \times 2/(2+6.02)$ hr = 1.5 hr

$T_{e_2} = 6.02 \times 3/(3+6.02)$ hr = 2.0 hr

$\tilde{A} = 245.3$ MBq.hr = 88.31×10^{10} Bq.s

$\tau = 2.45$ hr

Calculation of Ã

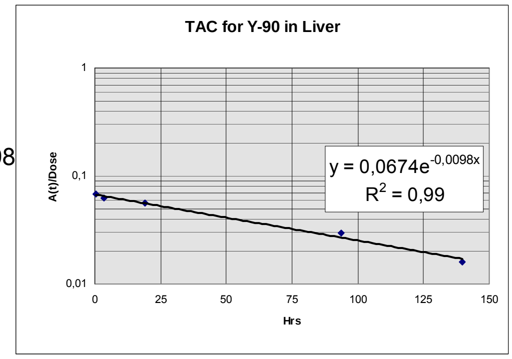
KU LEUVEN

- <u>Example</u>: uptake of ^{90}Y in the liver based on 5 measurements.
- Fit monoexponential and from this determine A(0) and T_e.

$A(t)/A_{injected} = 0.0674 \exp(-0.0098t)$

$A(0)/A_{injected} = 0.0674$; $T_e = \ln(2)/0.0098$

$\tau = T_e.A(0)/A_{injected} = 6.9$ hr



Calculation of Ã

KU LEUVEN

- Situation 3: uptake by the organ is not instantaneous (radionuclides that have a slow pattern of uptake in comparison to their physical half-life).

Uptake is described by $A(0).[1- \exp(-\ln(2).t/t_u)]$

Excretion by a half-life of T_b

Physical half-life: $t_{1/2}$

$A(t) = A(0).[1- \exp(-\ln(2).t/t_u)].\exp(-\ln(2).t/ t_{1/2}).\exp(-\ln(2).t/T_b)$

$\tilde{A} = T_e.(T_{ue}/T_u).A(0)/\ln(2)$ with $T_{ue} = T_u.T_e/(T_u+T_e)$

Calculation of Ã

KU LEUVEN

- Example: 250 MBq of a radioactive gas having a half-life of 20s is injected in an intravenous solution. It appears in the lungs with an uptake half-time of 30s and is excreted with a biological half-life of 10s. Uptake is described by ~ $1- \exp(-\ln(2).t/t_u)$

- The cumulated activity in the lungs is given by:

$\tilde{A} = T_e.(T_{ue}/T_u).250\text{MBq}/\ln(2)$

with $Te = 10 \times 20/(10+20)$ s = 6.7s

$T_{ue} = Tu.Te/(Tu+Te) = 30 \times 6.7/(6.7+30)$ s = 5.5s

$\tilde{A} = 6.7 \times (5.5/30) \times 250/\ln(2)$ MBq.s

$= 4.4\times10^8$ Bq.s

KU LEUVEN

MIRD method

1. The amount of activity and time in source and target organs
2. Total amount of radiation energy emitted by the radioactivity
3. Fraction of energy emitted by the source organ that is observed by the target organ

KU LEUVEN

Total amount of radiation energy emitted by the radioactivity

- Energy of the radionuclide emissions
- Number of desintegrations
- Physical properties

- Energy emitted per unit of cumulated activity is given by the equilibrium absorbed dose constant Δ.

Total amount of radiation energy emitted by the radioactivity

KU LEUVEN

- The factor Δ must be calculated for each type of emission for the radionuclide.

$$\Delta_i = 1.602x10^{-13}.N_i.E_i.k \quad [Gy.kg/Bq.s]$$

E_i is the average enery (in MeV) of the i^{th} emission

N_i is the relative frequency of that emission (number emitted by disintegration).

k = proportionality constant (Gy.kg/Bq.s.MeV)

- The product of cumulated activity Ã and equilibrium absorbed dose constant Δ_i is the radiation energy emitted by the i^{th} emission (in Gy.kg) during the time that the radioactivity is present in a source organ.

Example

KU LEUVEN

- A certain radionuclide decays by emitting β particles in 100% of its disintegrations with $\bar{E}_\beta$ = 0.3MeV.

  This is followed in 80% of its disintegrations by emission of a 0.2MeV γ-ray and in 20% by emission of a 0.195MeV conversion electron and a 0.005MeV characteristic X-ray.

- Calculation of Δ_β, Δ_γ, Δ_e, Δ_X
- E.g. Δ_γ = $1.602x10^{-13}.N_\gamma.E_\gamma.k$ [Gy.kg/Bq.s]

  = $1.602x10^{-13}$ x 0.8 x 0.2 Gy.kg/Bq.s

  = $2.56x10^{-14}$ Gy.kg/Bq.s

KU LEUVEN

MIRD method

1. The amount of activity and time in source and target organs
2. Total amount of radiation energy emitted by the radioactivity
3. Fraction of energy emitted by the source organ that is observed by the target organ

KU LEUVEN

Absorbed fraction ϕ

- The fraction of the energy emitted by the source organ that is absorbed by the target organ is given by the absorbed fraction $\phi_i(\text{target} \leftarrow \text{source})$ and it depends on
  - The amount of radiation energy reaching the target organ (tissue and distance attenuation)
  - Volume and composition of the target organ.
  - Type and energy of the i^{th} emission
  - Anatomic relationship of the source-target pair.
- The total energy emitted by the source organ and absorbed in a target organ is given by

$$D(\text{target} \leftarrow \text{source}) = \tilde{A}(\text{source}) . \Sigma_i . \phi_i(\text{target} \leftarrow \text{source}) . \Delta_i$$

KU LEUVEN

Average absorbed dose to the target organ

$$\overline{D} = \frac{1}{m_t} \sum_{\substack{source \\ organs}} \tilde{A}(source) \sum_i \phi_i(\text{target} \leftarrow \text{source}) \Delta_\text{i}$$

- S-values: the mean dose per unit cumulated activity

$$S(\text{target} \leftarrow \text{source}) = \frac{1}{m_t} \sum_i \phi_i(\text{target} \leftarrow \text{source}) \Delta_\text{i}$$

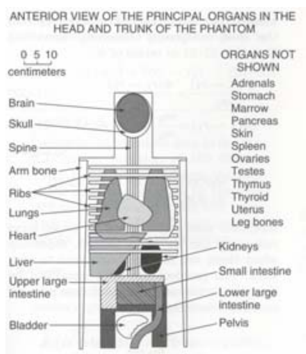
- Dose to the target organ

$$\overline{D} = \sum_{\substack{source \\ organs}} \tilde{A}(\text{source}) S(\text{target} \leftarrow \text{source})$$

KU LEUVEN

S-values

- Values of S have been calculated for mathematical humanoid models incorporating organs and anatomic structures of average size and shape.
- Phantoms: adult male and female, newborn, 1-year, 5-year, 10-year, 15-year old child, pregnant woman



Organ masses for the Cristy and Eckerman adult male phantom

KU LEUVEN

Organ	Mass (g)	Organ	Mass (g)
Adrenals	16.3	Ovaries	8.71
Brain	1420	Pancreas	94.3
Breasts (excluding skin)	351	Skeleton	
Gallbladder contents	55.7	Active marrow	1120
Gallbladder wall	10.5	Cortical bone	4000
Gastrointestinal tract		Trabecular bone	1000
Lower large intestine contents	143	Skin	3010
Lower large intestine wall	167	Spleen	183
Small intestine contents and wall	1100	Testes	39.1
Stomach contents	260	Thymus	20.9
Stomach wall	158	Thyroid	20.7
Upper large intestine contents	232	Urinary bladder contents	211
Upper large intestine wall	220	Urinary bladder wall	47.6
Heart contents	454	Uterus	79.0
Heart wall	316		
Kidneys	299	Remaining tissue	51,800
Liver	1910		
Lungs	1000		

Tabulated S-values

KU LEUVEN

S, MEAN DOSE PER UNIT CUMULATED ACTIVITY, (RAD/μCI-H) IODINE-131 — HALF-LIFE 193.0 HR

^{131}I

	Source organs									
			Skeleton							
Target organs	Ovaries	Pancreas	Red marrow	Cort. bone	Tra. bone	Skin	Spleen	Testes	Thyroid	Total body
Adrenals	1.4E-06	2.3E-05	6.1E-06	4.3E-06	4.3E-06	2.1E-06	1.8E-05	1.7E-07	5.2E-07	1.2E-05
Bladder wall	1.9E-05	5.0E-07	2.1E-06	1.6E-06	1.6E-06	1.7E-06	4.5E-07	1.4E-05	2.1E-08	1.1E-05
Bone (total)	2.9E-06	2.8E-06	2.5E-05	9.2E-05	6.5E-05	2.4E-06	2.3E-06	2.0E-06	2.2E-06	1.0E-05
G.I. (stomach wall)	2.3E-06	5.0E-05	2.9E-06	1.6E-06	1.6E-06	1.7E-06	2.7E-05	2.5E-07	2.6E-07	1.1E-05
G.I. (SI)	3.3E-05	5.1E-06	7.4E-06	2.2E-06	2.2E-06	1.5E-06	3.9E-06	1.4E-06	3.4E-08	1.1E-05
G.I. (ULI wall)	3.1E-05	6.1E-06	5.8E-06	2.0E-06	2.0E-06	1.5E-06	3.7E-06	9.7E-07	3.5E-08	1.1E-05
G.I. (LLI wall)	4.0E-05	1.5E-06	8.4E-06	2.8E-06	2.8E-06	1.6E-06	1.9E-06	7.8E-06	3.4E-08	1.1E-05
Kidneys	3.0E-06	1.8E-05	6.5E-06	2.6E-06	2.6E-06	2.0E-06	2.4E-05	2.4E-07	1.4E-07	1.1E-05
Liver	1.7E-06	1.2E-05	2.8E-06	1.9E-06	1.9E-06	1.8E-06	3.0E-06	1.4E-07	4.0E-07	1.1E-05
Lungs	2.7E-07	6.8E-06	3.4E-06	2.8E-06	2.8E-06	1.9E-06	6.2E-06	4.0E-08	2.9E-06	1.0E-05
Marrow (red)	9.8E-06	5.4E-06	2.3E-04	1.0E-05	1.0E-04	2.3E-06	3.5E-06	1.6E-06	2.4E-06	1.1E-05
Other tissues (muscle)	5.6E-06	5.0E-06	3.6E-06	3.0E-06	3.0E-06	2.4E-06	4.1E-06	3.4E-06	3.8E-06	9.8E-06
Ovaries	3.9E-02	1.1E-06	8.4E-06	2.6E-06	2.6E-06	1.1E-06	2.4E-06	0.0	4.1E-08	1.1E-05
Pancreas	1.5E-06	4.7E-03	4.6E-06	2.8E-06	2.8E-06	1.6E-06	5.4E-05	1.6E-07	2.4E-07	1.1E-05
Skin	1.4E-06	1.4E-06	2.0E-06	2.3E-06	2.3E-06	1.6E-04	1.6E-06	4.3E-06	2.4E-06	8.3E-06
Spleen	1.8E-06	5.4E-05	2.4E-06	2.2E-06	2.2E-06	1.8E-06	2.6E-03	2.3E-07	3.6E-07	1.1E-05
Testes	0.0	2.0E-07	1.1E-06	1.7E-06	1.7E-06	2.6E-06	2.4E-07	1.3E-02	7.2E-09	1.0E-05
Thyroid	4.1E-08	4.7E-07	2.3E-06	2.8E-06	2.8E-06	2.3E-06	3.8E-07	7.2E-09	2.2E-02	9.7E-06
Uterus (nongravida)	5.4E-05	1.8E-06	5.8E-06	1.7E-06	1.7E-06	1.4E-06	1.2E-06	0.0	3.8E-08	1.1E-05
Total body	1.2E-05	1.1E-05	1.0E-05	9.9E-06	9.9E-06	8.3E-06	1.1E-05	9.8E-06	9.5E-06	9.9E-06

1 rad/(mCi.hr) = 7.51×10^{-11} Gy/(Bq.s)

Whole-body dose, effective dose equivalent (H_E) and effective dose (E)

KU LEUVEN

To compare the dose of different nuclear medicine procedures: need for a single number.

Whole-body (or total body TB) dose $\bar{D}(TB) = \tilde{A}(TB).S(TB \leftarrow TB)$

Effective dose (E) and effective dose equivalent (H_E) represent the whole-body dose that would result in the same overall risk as a nonuniform dose distribution actually delivered. Differ only in the weighting factors W for the doses of different organs

Organ	$W(H_E)$	W(E)
Gonads	0.25	0.20
Red marrow	0.12	0.12
Colon	—	0.12
Lungs	0.12	0.12
Stomach	—	0.12
Bladder	—	0.05
Breasts	0.15	0.05
Liver	—	0.05
Esophagus	—	0.05
Thyroid	0.03	0.05
Skin	—	0.01
Bone surfaces	0.03	0.01
Remainder	0.30 split equally between five organs with highest dose	0.05 split equally between adrenals, brain, upper large intestine, small intestine, kidneys, muscle, pancreas, spleen, thymus, and uterus

Limitations of the MIRD formalism

KU LEUVEN

- Standard models (not patient specific)
- Assumed that the activity is distributed uniformly within each organ and that the energy is uniformly deposited throughout the organ
- Local radionuclide concentrations can be much higher than organ average calculations might suggest.

KU LEUVEN

Application 1: Radiation dose estimates for tracers used in nuclear medicine

KU LEUVEN

Example: radiation dose estimates for ^{18}F-FDG in an adult

Organ Dose	(mGy/MBq Administered)	Organ Dose	(mGy/MBq Administered)
Adrenals	1.3×10^{-2}	Muscle	1.1×10^{-2}
Brain	1.9×10^{-2}	Ovaries	1.7×10^{-2}
Breasts	9.2×10^{-3}	Pancreas	2.6×10^{-2}
Gallbladder wall	1.4×10^{-2}	Red marrow	1.3×10^{-2}
Lower large intestine wall	1.7×10^{-2}	Bone surfaces	1.2×10^{-2}
Small intestine	1.4×10^{-2}	Skin	8.4×10^{-3}
Stomach	1.3×10^{-2}	Spleen	3.7×10^{-2}
Upper large intestine wall	1.3×10^{-2}	Testes	1.3×10^{-2}
Heart wall	6.0×10^{-2}	Thymus	1.2×10^{-2}
Kidneys	2.0×10^{-2}	Thyroid	1.0×10^{-2}
Liver	1.6×10^{-2}	Urinary bladder wall	1.9×10^{-1}
Lungs	1.7×10^{-2}	Uterus	2.3×10^{-2}

Determined on normal subjects
Tables for many tracers used in nuclear medicine

KU LEUVEN

Application 2: Patient specific dosimetry in radio-immuno therapy (RIT)

KU LEUVEN

Introduction

- Ibritumomab tiuxetan (Zevalin) is a promising radio immunotherapy for lymphoma patients.
- Therapy: ^{90}Y-zevalin
  - ^{90}Y: decay (β-emission) to ^{90}Zr
  - $t_{1/2}$ = 64.0 hr
  - Average β-energy = 935 keV
- Dosimetry: ^{111}In-zevalin
  - ^{111}In: decay (EC) to ^{111}Cd
  - $t_{1/2}$ = 67.9 hr
  - $\gamma 1$ = 171 keV, $\gamma 2$ = 245 keV

KU LEUVEN

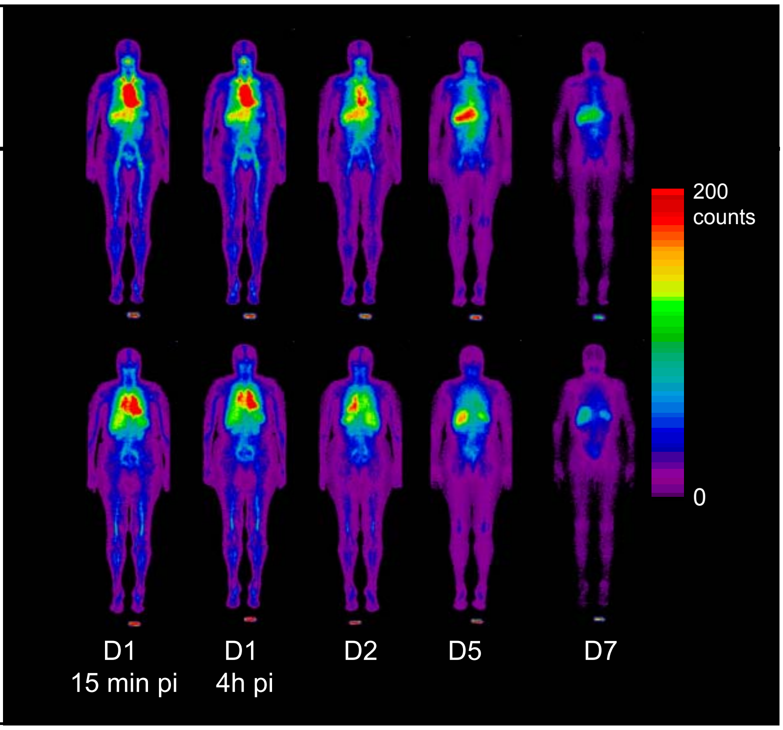
Acquisition

- 185 MBq ^{111}In-zevalin
- Dual-head gamma camera with medium-energy collimators
- 5 Planar whole body images
  - Day1: 15 min post injection and 3-6h post-injection
  - Day 2, 5 and 7
- Blood samples were taken immediately after each whole body scan.
- Imaging standard with a dose of 1.8 MBq was positioned just below the left foot.
- Blood samples and a standard of 20 kBq were measured in a well counter.

KU LEUVEN

anterior

posterior



MIRD formalism

KU LEUVEN

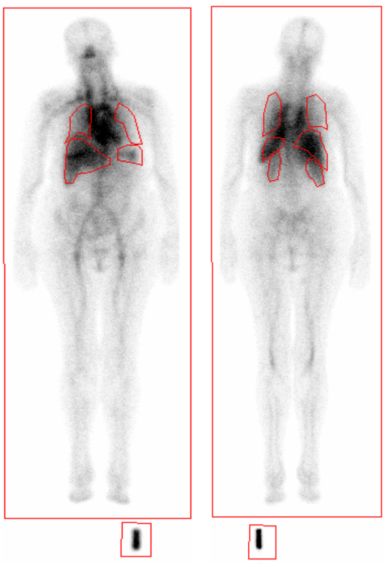
- Residence times were calculated for lungs, liver, spleen, kidneys, red marrow, whole body and the remainder.
- Radiation dose for the different organs was calculated using the MIRD formalism for a therapeutic dose of 14.8 MBq/kg ^{90}Y-ibritumomab tiuxetan (with a maximum dose of 1.2 GBq).

- Organs doses < 2000 cGy
- Bone marrow dose (the restrictive organ) < 300cGy

- Combination of patient specific data and models

ROI's

KU LEUVEN



Draw the same regions on every whole body image

copy the original region and translate/rotate

KU LEUVEN

input data

Anterior Scans

Scan Date & Time	Scan Duration (min.)	Counts in Region of Interest							
		Standard	Whole body	Lungs		Liver	Spleen	Kidneys	
				Right	Total			Right	Total
1/08/2002 14:14	**20**	**69042**	**4615106**		**276045**	**428062**	**73021**		**137608**
1/08/2002 17:09	**20**	**67883**	**4562162**		**261573**	**350020**	**67328**		**128201**
2/08/2002 8:55	**20**	**57214**	**3937523**		**214275**	**323272**	**59876**		**119167**
5/08/2002 11:33	**40**	**54359**	**3576074**		**148493**	**351417**	**58110**		**83561**
7/08/2002 9:43	**40**	**35048**	**2070676**		**72921**	**196064**	**34662**		**62548**

Posterior Scans

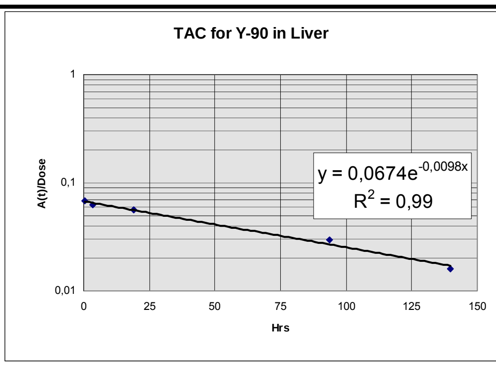
Scan Date & Time	Scan Duration (min.)	Counts in Region of Interest							
		Standard	Whole body	Lungs		Liver	Spleen	Kidneys	
				Right	Total			Right	Total
1/08/2002 14:14	20	**65328**	**4168082**		**358419**	**212271**	**103197**		**137608**
1/08/2002 17:09	20	**63640**	**4104905**		**306403**	**217412**	**114501**		**128201**
2/08/2002 8:55	20	**54188**	**3580350**		**215964**	**192762**	**94347**		**119167**
5/08/2002 11:33	40	**51832**	**3101930**		**162749**	**217729**	**67113**		**83561**
7/08/2002 9:43	40	**32117**	**1784893**		**77681**	**122069**	**43216**		**62548**

Calculation of the geometric mean = $(\text{value1} * \text{value2})^{1/2}$

KU LEUVEN

Calculation of residence times

Transfer data obtained from ^{111}In to ^{90}Y by taking the difference in half-life into account.



Fitting monoexponential: $A(t)/\text{Dose} = 0.0674 \exp(-0.0098t)$

$A(0)/\text{Dose} = 0.0674$ and $T_e = \ln(2)/0.0098$

Residence time = $\tilde{A}/\text{Dose} = T_e.A(0)/\text{Dose} = 6.9$ hr

Example: input data (blood data)

KU LEUVEN

- Blood samples will be 1 ml with water or saline added to bring to 5 ml
- ^{111}In standard will be 0.5 μCi with water or saline added to bring to 5 ml
- Counting window will be 140 to 550 keV
- Minimum counting time for standard and sample should produce >10^4 counts
- Background subtraction

Blood Sample Drawn:	Counting Data for Blood Sample		
	Start Time	Duration (min.)	Net CPM
1/08/2002 14:06	9/08/2002 9:31	1	301630
1/08/2002 17:03	9/08/2002 9:31	1	265519
2/08/2002 8:51	9/08/2002 9:31	1	200833
5/08/2002 10:02	9/08/2002 9:31	1	95502
7/08/2002 9:28	9/08/2002 9:31	1	65872

Counting standard activity:	0,398	μCi
Calibration time:	1/08/2002 18:10	

Counting Data for Standard		
Start Time	Duration (min.)	Net CPM
9/08/2002 9:31	1	68495

Residence time in red marrow (RM)

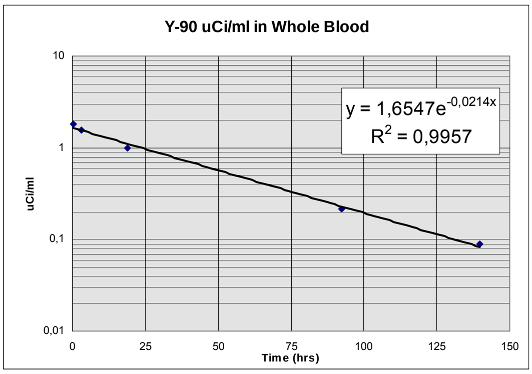
KU LEUVEN

- RM mass is assumed to be 1120 g for an adult male and 1050 g for a female
- Hematocrit value (as a fraction) should be known

$$T_{rm} = \frac{\frac{\tilde{A}_b}{m_b} \times m_{rm} \times \left(\frac{0.19}{1 - hemocrit}\right)}{uCi_{In-111}\ injected}$$

m_{rm} = RM mass

$\tilde{A}_b/m_b = T_{eb}.A_b(0)/m_b$



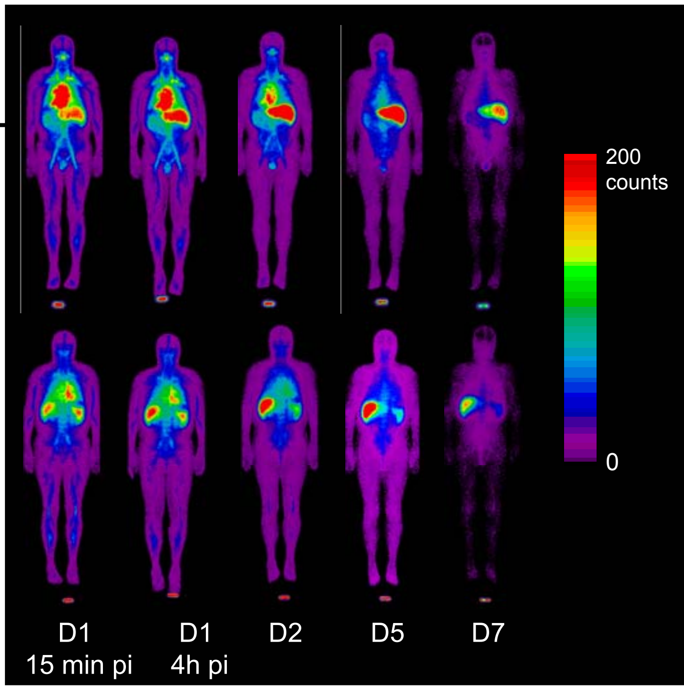
KU LEUVEN

Dosimetry calculations: result

Organ System	Residence Time (hrs)	Calculated Dose Factor cGy/MBq	Calculated Dose for 974.0 MBq cGy
Organs identified in protocol			
Kidneys	2,63	0,51	501
Liver	6,9	0,26	257
Lungs	4,42	0,30	290
Red Marrow	5,48	0,16	156
Spleen	1,74	0,63	610
Total Body	88,8	0,09	87
Remainder	73,2		
		0,00	
Other target tissues		0,00	
Bone surfaces		0,12	119
Unspecified organs		0,07	72

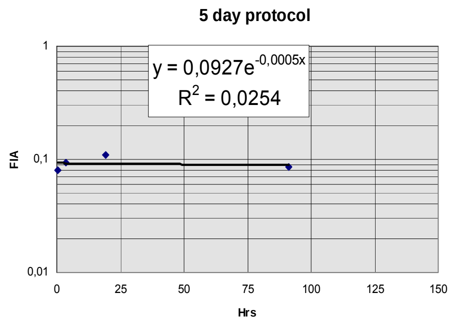
KU LEUVEN

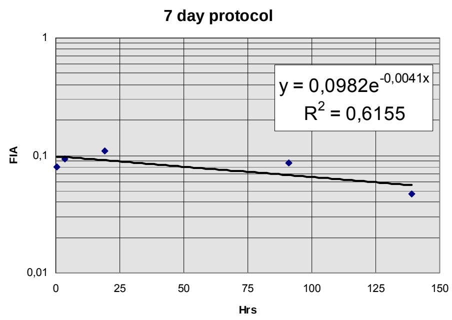
1 patient was showing a problem in the liver: high residence time



TAC in liver

KU LEUVEN





Estimated dose for liver: 6170 cGy 797 cGy

Bad fits of monoexponential.

^{90}Y-zevalin therapy was NOT given!

References and acknowdlegments

KU LEUVEN

- References:

  - Cherry, Sörenson and Phelps. Physics in nuclear medicine 3rd edition (Saunders, 2003)
  - Loevinger, Budinger and Watson. MIRD primer for absorbed dose calculations (Society for nuclear medicine, 1997)

- Acknowledgements

  - Sigrid Stroobants, Koen Van Laere, Shivani Ghoorun, Kristof Baete, Hubert Vanbilloen, Bruno Raes, Liesbet De Ceuninck