SOLUTIONS

Examination
Co-ordinating Radiation Protection Expert

Nuclear Research and Consultancy Group

	NRG
Delft University of Technology	TU Delft
Boerhaave CME/LUMC	BN/LUMC
University of Groningen	RUG
Radboudumc	RUMC
Eindhoven University of Technology	TU/e

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Problem 1 Shielding of a PET scanner

Question 1.1a

Determine the contribution to the effective annual dose resulting from all patients (P2 and P3) in both waiting areas at point A in the hallway. Disregard the shielding effect of the walls.

Waiting area 1 and 2:

- Distance to point A: r = 2.46 m. (Pythagoras)
- Average activity per 1 hour of a waiting patient:

  $A_{average} = A_0 \times cf_{decay} = 750 \times 0.832 = 624$ MBq
- Per patient: $H^*(10)_A = A_{average} \times h(10) \times t \times cf_{body\ shielding} / r^2 =$

  $624 \times 0.166 \times 1 \times 0.64 / 2.46^2 = 10.95$ μSv
- Contribution of waiting area 1:

  [Number of patients] x $H^*(10)_A = 750 \times 10.95 = 8213$ μSv/y
- Contribution of waiting area 2 = 8213 μSv/y = 8.2 mSv/y.

effective dose in A as a result of both waiting areas:

= 8.2 + 8.2 = 16.4 mSv/y.

Question 1.1b

Now determine the contribution to the effective annual dose at point A resulting from the patients who are scanned with the PET scanner under the same conditions as in question 1.1a.

Scanner room:

- Distance to point A = 2.50 m
- Average activity per patient during 30 min. of examination:

  $A_{average} = A_{start} \times cf_{decay}$

  A_{start} (after 1 hour) = $A_0 \times e^{(-0.693 \times 60/109.7)}$ (=decay after 1 hour) x $cf_{urination}$ =

  $750 \times 0.685 \times 0.70 = 359.6$ MBq

  $A_{average} = 359.6 \times 0.911 = 327.6$ MBq
- Per patient:

  $H^*(10)_A = A_{average} \times h(10) \times t \times cf_{body\ shielding} \times cf_{scanner\ shielding} / r^2 =$

  $327.6 \times 0.166 \times 0.50 \times 0.64 \times 0.90 / 2.5^2 = 2.51$ μSv

Contribution of the scanner room:

[Number of patients] x $H^*(10)_A$ = 1500 x 2.51 = 3765 μSv/y

= 3.8 mSv/y

Question 1.1c

Demonstrate that the total contribution to the effective dose for a person at point A – in the case of an occupancy rate of 0.2 – is equal to 4 mSv/y.

Total effective dose at A:

(16.4[question 1a] + 3.8[question 1b]) x 0.2[persistence factor]= 4(.0) mSv/y

Question 1.2

Demonstrate that the amount of lead shielding (in whole mm) required in the walls on the hallway side to keep the total effective annual dose for a person at point A below 1 mSv amounts to approximately 10 mm. Take the occupancy rate of this hallway into account. As a starting point, assume that the transmission from the scanner room is equal to the transmission from the waiting areas.

Use Table 1 (broad beam) for the transmission factors.

Required transmission factor: T = 1 / (4) = 0.25

Read in Table 1: 10 mm of lead.

Question 1.3

With the help of Figure 2 and Table 2, calculate the transmission for 10 mm of lead shielding and determine if this transmission deviates more or less than 10% from the value previously determined in Question 1.2.

Figure 2 shows that the half-value layer for narrow beams is approx. 4 mm of lead with 511 keV.

$\mu \cdot d_{½} = \ln 2 = 0.693$

$d_{½} = 4$ mm

Therefore: $\mu = 0.173\ \text{mm}^{-1}$

The following applies to a lead thickness of 10 mm: $\mu \cdot d = 0.173 \times 10 = 1.73$.

According to Table 2 and interpolation, the build-up factor is:

B = 1.24 + 0.73 (1.42–1.24) = 1.37

The transmission for lead in this situation amounts to:

$T = B \cdot e^{-\mu.d} = 1.37 \cdot e^{-1,73} = 0.24$

Ten per cent of the value found in Question 1.2 amounts to 0.025. The difference between the transmissions found is 0.01. Conclusion: deviation is less than 10% and both methods lead to virtually the same transmission value.

Question 1.4

Argue that the total contribution to the effective annual dose at point B exceeds 1 mSv in the control room if the wall between the control room and the scanner room has the same transmission as the walls in the hallway.

As a result of the scanner room, 3.8 (3.77) mSv/y was found (Question 1a) at point A (2.5 m).

- Distance to point B is 1.5 m
- A wall is penetrated once, so T= 0.25

$3.77 \text{ mSv/y} \times 0.25 \times (2.5/1.5)^2 = 2.6 \text{ mSv/y}$

This is already higher than 1 mSv – contributions from waiting areas increase this amount even further.

Scoring:

Problem	
Question	**Points**
1a	4
1b	3
1c	2
2	2
3	4
4	2
Total	**17**

Problem 2 Dietary salt

Question 2.1

Based on the most important emitted radiation types of ^{40}K, provide a possible reason for why the measurement with the GM tube shows a clear increase.
In addition, provide a possible reason for why the measurement with the NaI crystal does not show an increase.

The most important emitted radiation is:
β^- with a yield = 0.893 = 89.3% and an E_{max} = 1312 keV
γ_1 with a yield = 0.107 = 10.7 % and an E = 1461 keV
[The Auger electrons with an E = 3 keV mentioned in Keverling Buisman will not be detected anyway with this type of detection 'at a distance'].

GM tube filled with gas. The βs have a high E_{max}, slightly lower than, for example, ^{32}P. These types of charged particles can easily be detected with a GM tube. This explains the signal of the GM tube.

NaI crystal, no signal:
The mass activity is already very low, but the GM tube still indicated an increase.
The βs, charged particles, do not interact in the NaI crystal. Most βs will already be blocked in the casing of the crystal. Any single β (originally the hardest) that might succeed in passing through the casing would have already lost a great deal of energy. Causes few, if any, scintillations.
The NaI signal should come from the 10.7% γ with an energy value of 1461 keV. 1st. This yield is low, only 10.7%. 2nd. And this gamma energy is very high, even higher than, for example, the gamma energy of ^{60}Co. The penetrating capacity of this gamma energy is very high. Apparently, the number of interactions is so low that no signal is given.

It is essential that the following matters be included in the answer:
1) the GM tube detects the βs. And
2) the NaI hand monitor can be expected to measure the γs, but
3) this apparently does not occur due to the small amount and the very high energy level. There are not enough interactions in the NaI detector material.

Question 2.2

Calculate the measurement capacity of this measurement in cps/Bq. In addition, calculate the standard deviation in this measurement capacity.

No dead-time correction is necessary for a counting speed of approximately 1.00 cps (994 counts in 999 seconds).

$$R_{netto} = \frac{994\ \text{(counts)}}{999\ \text{(s)}} - \frac{499\ \text{(counts)}}{999\ \text{(s)}} = 0{,}995\ \text{(cps)} - 0{,}499\ \text{(cps)} = 0{,}496\ \text{cps}$$

A = 0.535 (g dietary salt) × 0.973 (g KCl/g dietary salt) × 16.2 (Bq/g KCl) = 8.43 Bq

Measurement capacity $\varepsilon = \frac{0{,}496\ \text{(cps)}}{8{,}43\ \text{(Bq)}} = 0{,}0588$ cps/Bq

$$\sigma_R = \sqrt{\frac{R_a}{t_a} + \frac{R_b}{t_b}} = \sqrt{\frac{0{,}995}{999} + \frac{0{,}499}{999}} = \sqrt{\frac{0{,}995 + 0{,}499}{999}} = 0{,}0387\ \text{cps}$$

$$\sigma \text{ in } \varepsilon = \frac{0{,}0387\ \text{(cps)}}{8{,}43\ \text{(Bq)}} = 0{,}0046\ \text{cps/Bq}$$

Extra:

1 σ = 0.0046 (cps/Bq)/0.0588 (cps/Bq) × 100% = 7.8%

Alternative:

1 σ = 0.0387 (cps)/0.496 (cps) × 100% = 7.8%

In percentages, the standard deviation in the measurement capacity of 0.0588 cps/Bq corresponds to 7.8%.

Question 2.3

Demonstrate with a calculation that the NaI measurement with the dietary salt in the fixed set-up is now significantly higher than the background measurement (with a reliability interval of 99.7%).

The background measurement yields 104,589 counts; σ = √104,589 = 323 counts

The background measurement + 1 σ = 104,912 counts
The background measurement + 3 σ = 105,558 counts

The measurement with dietary salt yields 121,526 counts

The result of the measurement of the dietary salt is much higher than the [background + 3 σ].
In other words: significant increase, highly demonstrable.

Question 2.4

Determine the capacity of the measurement with this fixed NaI set-up in counts per second/photons per second (cps/pps).

R_{net} = 121,526 (counts) – 104,589 (counts) =
16,937 (counts) per 72,000 (s) = 0.235 cps.

A = 3.08 (g dietary salt) × 0.973 (g KCl/g dietary salt) × 16.2 (Bq/g KCl) = 48.5 Bq = 48.5 disintegrations per s

0.107 (photons/disintegration) × 48.5 (disintegrations/s) = 5.19 pps

ε = 0.235 (cps)/5.19 (pps) = 0.045 cps/pps

Scoring:

Problem	
Question	**Points**
1	3
2	5
3	3
4	4
Total	***15***

Problem 3 Unanticipated consequence of iodine therapy

Question 3.1

How many days after the application of the iodine therapy will the monitor still trigger an alarm at the airport? Shielding by the body tissue of the man can be considered negligible and therefore disregarded.

$1/T_{½,eff} = 1/T_{½,biol} + 1/T_{½,phys} = 1/90\ (d) + 1/8.021\ (d) = 0.136\ d^{-1}$

$\rightarrow\ T_{½,eff} = 7.36\ d$

direct excretion = 70% = 0.70

$H^* = 0.066\ (\mu Sv/h\ per\ MBq/m^2) \times 400\ (MBq) \times (1 - 0.70) \times e^{-0.693 \times t/7.35\ (d)}$

$\quad / (0.5\ m)^2$

$\quad = 32 \times e^{-0.693 \times t/7.36\ (d)}\ \mu Sv/h$

$\quad = 0.005\ \mu Sv/h$

$t = (7.36\ (d) / 0.693) \times \ln(32 / 0.005) = 93\ d$

Question 3.2 a

Calculate the number of disintegrations $U_{thyroid}$ (in Bq·s) in the thyroid gland.

$T_{½,eff} = 7.36\ d$

$U_{thyroid} = A_{ingestion} \times f_{thyroid} \times {}_0\int^{\infty} e^{-0.693 \times t/T(½,eff)}\ dt = A_{ingestion} \times f_{thyroid} \times T_{½,eff}\ /0.693$

$\quad = 400 \cdot 10^6\ (Bq) \times 0.30 \times 7.36\ (d) \times 24\ (h/d) \times 3600\ (s/h) / 0.693$

$\quad = 1.10 \cdot 10^{14}\ Bq \cdot s$

Question 3.2b

Using the answer to Question 3.2a, calculate the dose $D_{thyroid}$ absorbed by the thyroid gland. If you were unable to obtain the answer to Question 3.2a, use 10^{14} disintegrations.

$D_{thyroid} = U_{thyroid} \times SEE_{thyroid}$

$SEE_{thyroid} = 1.60 \cdot 10^{-19}\ (J/eV) \times [E_{\beta,gem} \times y]\ (eV/Bq \cdot s)\ / m_{thyroid}\ (kg)$

$\quad = 1.60 \cdot 10^{-19}\ (J/eV) \times 0.192 \cdot 10^6 \times 0.894\ (eV/Bq \cdot s) / 20 \cdot 10^{-3}\ (kg)$

$\quad = 1.37 \cdot 10^{-12}\ Gy\ per\ Bq \cdot s$

$D_{thyroid} = U_{thyroid} \times SEE_{thyroid}$

$\quad = 1.10 \cdot 10^{14}\ (Bq \cdot s) \times 1.37 \cdot 10^{-12}\ (Gy/Bq \cdot s)$

$\quad = 1.5 \cdot 10^2\ (Gy)$

The fictitious number of disintegrations yields $D_{thyroid} = 1.4 \cdot 10^2\ (Gy)$

Question 3.3

Determine the committed effective dose for the man. In addition, demonstrate with a calculation that most of this committed effective dose is determined by the dose absorbed in the thyroid gland (use the answer to Question 3.2b in your calculation).

It can be assumed that the information from the *Handboek Radionucliden* [Radionuclides Handbook] can also be used for this patient. On the basis of this information, the following calculation can be made:

$E(50)_{ing} = A \times e(50)_{ing}(b) = 400\ \text{MBq} \times 2.2 \cdot 10^{-8}\ \text{Sv/Bq} = 8.8\ \text{Sv}$
(Note that committed effective doses of around 8 Sv do not have the usual definition, but the calculation for lesser activities is identical.)

The contribution of the thyroid gland to $E(50)_{ing}$ is derived from $D_{thyroid}$ by means of multiplication by the tissue weighting factor for the thyroid gland: $w_T = 0.05$.
$E(50)_{ing,thyroid}$ **=** $1.5 \cdot 10^{2}$ (Gy) × 0.05 = 7.5 Sv. This contribution is 86% of the value of $E(50)_{ing}$ calculated above.

Question 3.4

Estimate the effective dose that the woman receives in the nights following the iodine therapy as a result of the ^{131}I activity. State the assumptions required to make this estimation.

The assumptions to be made. Estimate the transmission (approve T = 1). Estimate the distance (approve everything in the range of 0.3 - 1.2 m). Apply a point source approach. Approve all assumptions for ‘sleep moments’. Only punish nonsense.

Example:
T = 0.8
$H^* = h \times A(t=0) \times {}_0\int^{\infty} e^{-0.693 \times t/7.35\ (d)}\, dt \times (1 - 0.70) \times f \times B \times T / r^2$
in this calculation, f is the fraction of the time that the woman was exposed
${}_0\int^{\infty} e^{-0.693 \times t/7.36\ (d)}\, dt = 7.36\ (d) \times 24\ (h/d) / 0.693 = 255\ h$
exposure lasts 8 hours a day, so f = 8 (h) / 24 (h) = 0.33
$H^* = 0.066\ (\mu Sv/h\ \text{per}\ MBq/m^2) \times 400\ (MBq) \times 255\ (h) \times$
$0.3 \times 0.33 \times 0.80 / (0.5\ m)^2 = 2.1 \cdot 10^{3}\ \mu Sv = 2.1\ mSv$

Scoring:

Problem	
Question	**Points**
1	4
2 a	3
2b	3
3	3
4	4
Total	**17**

Problem 4 Veterinary practice

Question 4.1

Demonstrate that the entry dose of a single scan at the level of the scattering surface is equal to 2.8 mGy.

V = 75 kV; k = 6.1 mGy·m^2/(mA·min);

I × t = 10 mA·s=10 (mA·s)× 1 (min) / 60 (s)=0.17 mA·min;

r = 0.6 m;

$$D \approx K_{in} = \frac{k \times I \times t}{r^2} = \frac{6{,}1\ (\mathrm{mGy \cdot m^2/(mA \cdot min)}) \times 0{,}17\ (\mathrm{mA \cdot min})}{(0{,}6\ (\mathrm{m})\ )^2} = 2{,}8\ \mathrm{mGy}$$

Question 4.2

Determine the maximum effective dose per year behind the lead apron at the level of the veterinarian.

K_{in} =2.8 mGy;

scattering angle is 90 degrees; scattering surface is 500 cm^2;

scattering fraction of air kerma: (for 75 kV = 0.075 MV =) 0.15% per 100 cm^2 at 0.5 m (water). This is equal to a scattering fraction of 0.038% per 100 cm^2 at 1 metre.

Number of photographs: 1000

Transmission:

$k_{0.5\ mm\ Pb}$= $k_{0.05\ cm\ Pb}$ = 0.1 mGy·m^2/(mA·min);

$k_{0\ mm\ Pb}$=6.1 mGy·m^2/(mA·min);

T = 0.1 / 6.1 = 0.016;

$$K = \frac{K_{in} \times 0{,}038 \cdot 10^{-2} (\mathrm{m^2}) \times T \times \frac{500\ (\mathrm{cm^2})}{100\ (\mathrm{cm^2})} \times 1000}{r^2}$$

$$= \frac{2{,}8\ (\mathrm{mGy}) \times 0{,}038 \cdot 10^{-2} (\mathrm{m^2}) \times 0{,}016 \times \frac{500\ (\mathrm{cm^2})}{100\ (\mathrm{cm^2})} \times 1000\ (\mathrm{j^{-1}})}{\left(0{,}20\ (\mathrm{m})\right)^2}$$

$$= 2{,}1\ \mathrm{mGy/j}$$

Radiation weighting factor of X-ray radiation: 1

Tissue weighting factor of the total body irradiation: 1

$$E = D \times w_R \times w_T \approx K \times w_R \times w_T = 2{,}1\ [\mathrm{mGy}] \times 1 \times 1 = 2{,}1\ \mathrm{mSv}$$

Question 4.3

Determine the equivalent annual dose resulting from this anticipated unintended event for both hands of the veterinarian when the mentioned lead gloves are used, and indicate whether or not the legal limit for an exposed employee is exceeded.

$D \approx K_{in} = 2{,}8\ \mathrm{mGy}$ (question 1);

T= 100% - 40% (protection factor)= 60%;

Radiation weighting factor of X-ray radiation: 1;
Frequency: 1000/10 = 100 years^{-1}

$$H_{huid} = D \times T \times w_R \approx K \times T \times w_R \times f = 2{,}8\ (\mathrm{mGy}) \times 0{,}60 \times 1 \times 100 = 170\ \mathrm{mSv}$$

This equivalent skin dose is under the legal limit of 500 mSv.

Question 4.4

Explain why the dose reduction of the lead gloves is lower in the case of exposure to the primary beam (40%) than in the case of exposure to the scattered radiation (secondary beam, 80%).

Compton-scattered radiation has a longer average energy level than radiation in the primary beam, because the primary beam interacts with the material, causing it to lose energy while being scattered.

Due to its higher average energy level, primary radiation is harder to shield than scattered radiation with its lower average energy level. The use of lead gloves in the primary beam therefore has a lower protection factor than the use of lead gloves in scattered radiation.

Scoring

Problem 4	
Question	**Points**
1	3
2	5
3	4
4	2
Total	***14***