Dollars and Sense: Are We Overshielding Imaging Facilities? Part 2

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Disclosure

- Paid consultant to NELCO Worldwide
- Owner, CEO ZapIT! Medical

Objectives

- Understand methods for calculating shielding requirements in nuclear medicine and facilities
- Review sample shielding specifications for typical nuclear medicine/PET room
- Understand methods and assumptions for performance of area surveys of imaging facilities
- Compare costs of varying shielding materials as well as effect of shielding factors on cost of shielding imaging facilities

General Nuclear Medicine Shielding

- Factors for determining shielding requirement

$$B_{x_{barrier}} = \left(\frac{P}{T}\right)\frac{d^2}{K^1 N}$$

  - Must include transmission factors for all radionuclides
  - K includes unshielded equivalent dose for all radionuclides

General Nuclear Medicine Shielding

- Options for determining transmission factors
  - Use published broad beam 1st TVL data

$$TF_{TVL}(x) = 10^{\left(-\frac{x}{TVL}\right)}$$

  - Consider μ and exposure buildup factors for each radionuclide energy

$$TF_{B,i}(x) = exp(-\mu_i x)B(x)_i$$

Reference: Kusano, M., Caldwell, CB "Dose equivalent rate constants and barrier transmission data for nuclear medicine facility dose calculations and shielding design", Health Phys. 2014 Jul;107(1):60-72

General Nuclear Medicine Shielding

- Factoring μ and buildup factors, curves fit to the mathematical model proposed by Archer, et.Al (1983) for common isotopes

Table 7. Archer fitting parameters for transmission factor (TF) through lead for seven radionuclides commonly used in nuclear medicine.

Nuclide	Archer parameters α (mm⁻¹)	β (mm⁻¹)	γ	χ^2
Ga-67	0.04412	0.7326	0.3869	0.2644
I-123	0.1322	14.85	1.488	0.7361
I-131	0.1078	0.2003	0.4957	0.1061
In-111	0.7094	30.63	5.979	0.0890
Tc-99m	2.479	−1.093	1.376	0.0011
Tl-201	1.670	1.358	0.3692	0.0160
Xe-133	2.660	55.84	2.419	0.1597

*Note: $TF = \left[\left(1+\frac{\beta}{\alpha}\right)\exp(\alpha\gamma x)-\frac{\beta}{\alpha}\right]^{-1/\gamma}$

Kusano and Caldwell, (2014)

General Nuclear Medicine Shielding

- Unshielded equivalent dose

$$H(\mu Sv) = \frac{D_{\delta st} A_0 F_1 t_2 R_{t2}}{d^2}$$

- $D_{\delta st}$ easily estimated by multiplying published air kerma rates by radionuclide-specific factors relating response of tissue to spectra range

Kusano and Caldwell, (2014)

General Nuclear Medicine Shielding

Table 1. The dose equivalent rate constant for ^{99m}Tc derived from reported exposure and air kerma rate constants.

Reference	Exposure rate constant (R cm^2 mCi^{-1} h^{-1})	Air kerma rate constant (μGy m^2 GBq^{-1} h^{-1})	Conversion factor	Derived dose equivalent rate constant (μSv m^2 GBq^{-1} h^{-1})
NCRP 124 (1996)	—	20	1.1[a]	22
Wasserman and Groenewald (1998)	0.6	14.2	1.1	15.6
Ninkovic et al. (2005)	—	14.10	1.11	15.7
Smith and Stabin (2012)	0.795	N/A	0.959 cGy/R	20.6

[a]Value chosen by the authors.

Kusano and Caldwell, (2014)

General Nuclear Medicine Shielding – Calculating the required shielding

$$B_x = \frac{P}{H_i}$$

$$x = \frac{1}{\alpha\gamma} ln\left(\frac{B^{-\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}}\right)$$

NCRP 147

Typical Scan Room

- Bone Scans only : Tc-99m
- 500 patients per year
- 3 m from patient
- 23 mCi (0.85 GBq) dose, 3.0 hour uptake time and 45 minute scan time

- Using $D_{\delta st}$ of 16.1 (Kusano and Caldwell) = 0.9 mm Pb
- Using $D_{\delta st}$ of 22 (NRP 124) = 1.0 mm Pb

Typical Scan Room

- All scans
- 1900 patients per year
- 3 m from patient

Table 2. Hypothetical nuclear medicine scan room procedures used to test the effect of differences in dose rate constants and transmission factors in a practical scenario.

Scan room procedure	Nuclide	Procedures per year N	Administered activity A_0 (GBq)	Uptake time t_1 (h)	Scan time t_2 (h)	Percentage of scan room workload[a]
Bone scan	Tc-99m	500	0.85	3	0.75	56%
Cardiac perfusion—rest scan	Tc-99m	500	0.37	1	0.33	8%
Cardiac perfusion—stress scan	Tc-99m	500	1.11	1	0.33	24%
Gallium oncology	Ga-67	50	0.296	72	1.5	3%
I-123 MIBG	I-123	50	0.296	24	1.5	3%
Whole body I-131	I-131	50	0.111	72	1.5	1%
Octreotide	In-111	50	0.222	4 (scan 1)	1.5 (scan 1)	4%
				24 (scan 2)	1.5 (scan 2)	4%
Cardiac viability	Tl-201	50	0.111	0.17 (scan 1)	0.33 (scan 1)	0.2%
				3 (scan 2)	0.33 (scan 2)	0.2%
Lung Ventilation	Xe-133	50	0.555	0	0.25	1%

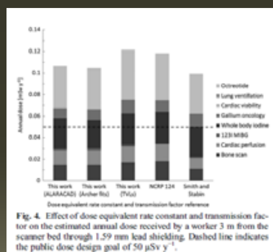
[a]Approximate percentage of scan room workload = $(N \times A_0 \times t_2)_{procedure} / \Sigma(N \times A_0 \times t_2) \times 100\%$.

Kusano and Caldwell, (2014)

General Nuclear Medicine Shielding – Practical results

Procedure	Isotope	T1/2 (hr)	Dδst	A0 (GBq)	Bx	alpha	Beta	Gamma	x
Bone Scan	tc-99m	6.03	16.1	0.85	0.159503	2.479	-1.093	1.376	0.900425
Cardiac Rest	tc-99m	6.03	16.1	0.37	0.609758	2.479	-1.093	1.376	0.295975
Cardiac Stress	tc-99m	6.03	16.1	1.11	0.205246	2.479	-1.093	1.376	0.79839
Gallium	Ga-67	78	20.85	0.296	1.63564	0.04412	0.7326	0.3869	0
I-123 MIBG	I-123	13.2	41.57	0.296	1.101111	0.1322	14.85	1.4880	0
Whole Body I-131	I-131	192	57.44	0.111	1.822862	0.1078	0.2003	0.4957	0
Octreotide Scan1	In-111	67.2	83.14	0.222	0.412843	0.7094	30.63	5.979	0.400417
Octreotide Scan2	In-111	67.2	83.14	0.222	0.456557	0.7094	30.63	5.979	0.291002
Cardiac Viability	Tl-201	73.1	11.29	0.111	26.93125	1.67	1.358	0.3692	0
Cardiac Viability	Tl-201	73.1	11.29	0.111	27.29404	1.67	1.358	0.3692	0
Lung Ventilation	Xe-133	125.76	13.87	0.555	5.777766	2.66	55.84	2.419	0

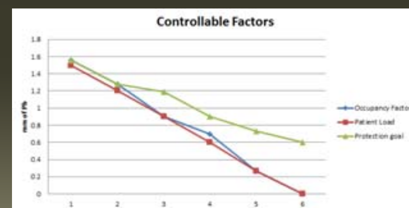
General Nuclear Medicine Shielding – Reference Comparison



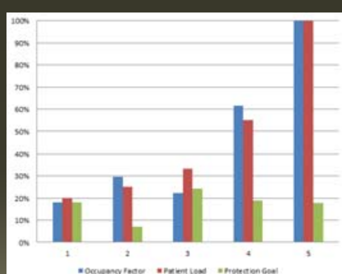
Kusano and Caldwell, (2014)

General Nuclear Medicine Shielding – Factor comparison

- Occupancy factors 1.0 through 1/40
- Number of patients N=40 to N=1 per week
- Protection Level: 1, 2, 2.5, 5, 7.5 and 10 mSv



General Nuclear Medicine Shielding – % Reduction in Required Shielding



Which of the following must be considered in determining shielding requirements for nuclear medicine facilities?

20%	1. Dose equivalent rate constants for soft tissue
20%	2. Barrier transmission factors for alpha particles
20%	3. Air kerma rates for the most common radionuclide used in the department
20%	4. Barrier transmission factors for the radionuclide with the highest energy
20%	5. Total number of administrative FTE's in the department

10

Answer: A

The dose equivalent rate constant and transmission factors for all radionuclides used in the department must be evaluated

Reference: Kusano, M., Caldwell, CB "Dose equivalent rate constants and barrier transmission data for nuclear medicine facility dose calculations and shielding design", Health Phys. 2014 Jul;107(1):60-72

Dose equivalent rate constants for soft tissue can vary by as much as what percentage depending on the available literature?

20%	1. 40%
20%	2. 10%
20%	3. 75%
20%	4. 100%
20%	5. They're all about the same

10

Answer: A

Varying published air kerma data and energy threshold for certain isotopes can significantly affect the dose equivalent rate constant

Reference: Kusano, M., Caldwell, CB "Dose equivalent rate constants and barrier transmission data for nuclear medicine facility dose calculations and shielding design", Health Phys. 2014 Jul;107(1):60-72

PET Shielding

- PET imaging follows same method

TABLE VI. Summary of dose parameters.

Parameter	Definition	Formulation
A_0	Administered activity (MBq)	
t	Time (h)	
t_U	Uptake time (h)	
t_I	Imaging time (h)	
$D(t)$	Total dose for time t (μSv)	
$D(0)$	Initial dose rate (μSv/h)	
$T_{1/2}$	Radionuclide half-life (h)	
R_t	Dose reduction factor over time t	$=1.443\times(T_{1/2}/t)\times[1-\exp(-0.693t/T_{1/2})]$
R_{tU}	Dose reduction factor over uptake time time t	$=1.443\times(T_{1/2}/t_U)\times(1-\exp(-0.693t_U/T_{1/2}))$
R_{tI}	Dose reduction factor over imaging time t	$=1.443\times(T_{1/2}/t_I)\times[1-\exp(-0.693t_I/T_{1/2})]$
N_w	Number of patients per week	
d	Distance from source to barrier (m)	
F_U	Uptake time decay factor (μSv)	$=\exp[-0.693t_U/T_{1/2})]$
T	Occupancy factor	
P	Weekly dose limit	
	Transmission factor (uptake room)	$=10.9\times P\times d^2/[T\times N_w\times A_0\times t_U(h)\times R_{tU}]$
B	Transmission factor (scanner room)	$=12.8\times P\times d^2/[T\times N_w\times A_0\times F_U\times t_I(h)\times R_{tI}]$

Reference: Madsen, M., et. Al., AAPM Task Group 108: PET and PET/CT Shielding Requirements, Med. Phys. 33 (1) January 2006

PET Shielding - Factors

- Which Isotope?

TABLE I. Physical properties of commonly used PET radionuclides.

Nuclide	Half-life	Decay mode	Positron maximum energy(MeV)	Photon emission(keV)	Photons/decay
^{11}C	20.4 min	$\beta+$	0.96	511	2.00
^{13}N	10.0 min	$\beta+$	1.19	511	2.00
^{15}O	2.0 min	$\beta+$	1.72	511	2.00
^{18}F	109.8 min	$\beta+$, EC	0.63	511	1.93
^{64}Cu	12.7 h	$\beta-$, $\beta+$, EC	0.65	511, 1346	0.38, 0.005
^{68}Ga	68.3 min	$\beta+$, EC	1.9	511	1.84
^{82}Rb	76 s	$\beta+$, EC	3.35	511, 776	1.90, 0.13
^{124}I	4.2 d	$\beta+$, EC	1.54, 2.17	511, 603, 1693	0.5,0.62,0.3

- TG-108 recommends F-18
  - Most widely used
  - Relatively long half-life

Madsen, 2006

PET Shielding - Factors

- Dose equivalent rate constants for F-18

TABLE III. Reported values of F-18 exposure and dose rate constants.

F-18 rate constants	Value	Units
Exposure rate constant	15.4	μR m^2/MBq h
Air kerma rate constant	0.134	μSv m^2/MBq h
Effective dose equivalent (ANS-1991)	0.143	μSv m^2/MBq h
Tissue dose constant[a]	0.148	μSv m^2/MBq h
Deep dose equivalent (ANS-1977)	0.183	μSv m^2/MBq h
Maximum dose (ANS-1977)	0.188	μSv m^2/MBq h

[a]Dose to 1 cm^3 of tissue in air.

- TG-108 recommends the effective dose equivalent value of 0.143 μSvm^2 / MBqh

Madsen, 2006

PET Shielding - Factors

- Broad beam transmission

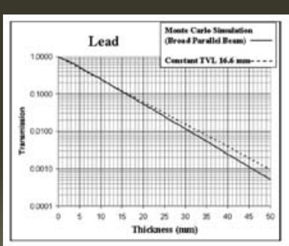


FIG. 1. Plot of lead broad beam transmission factors as a function of lead thickness.

Madsen, 2006

PET Shielding - Factors

- The Monte Carlo calculated transmissions values can be fit to the Archer model by optimizing the parameters as shown

TABLE V. Fitting parameter for broad beam 511 keV transmission data.

Shielding material	α(cm^{-1})	β(cm^{-1})	γ
Lead	1.543	−0.4408	2.136
Concrete	0.1539	−0.1161	2.0752
Iron	0.5704	−0.3063	0.6326

Madsen, 2006

PET Shielding – Calculating the required shielding

$$B_x = \frac{P}{H_i}$$

$$x = \frac{1}{\alpha\gamma} ln\left(\frac{B^{-\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}}\right)$$

NCRP 147

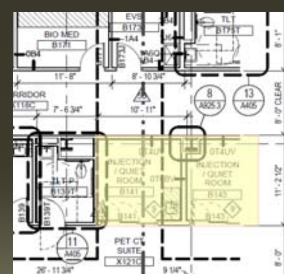
PET Shielding – Factors affecting shielding calculation

- Patient attenuation
  - Direct exposure measurements at various locations
  - Averaged after normalizing for administered activity and distance
  - **0.092 μSv m² / MBq h**
- Administered activity can vary
  - Philips recommends weight based activity up to 20 mCi

PET Shielding – Uptake room versus imaging room

- Conservatively, gantry attenuation ignored but may be 20%
  - Due to setup time may be more like 15%
- Patient voids prior to imaging
  - 15% reduction in dose rate
- Uptake time >> imaging time

Typical PET-Scan Calculation – Uptake Rooms



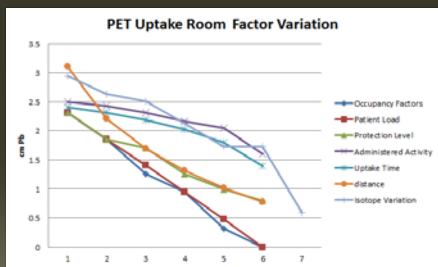
Typical PET-Scan Calculation – Uptake Rooms

- 15 mCi injections
- 80 patients / week
- Assume chair in middle of room
- 4 rooms – assume 50% of patient load in each room
- Uptake time = 1.25 hours
- Protect to public dose

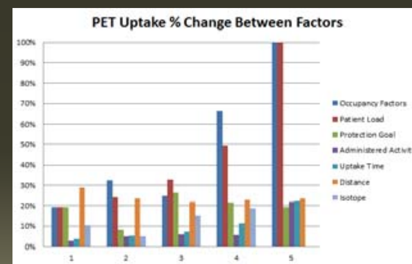
PET-Uptake Room Shielding – Factor comparison

- Occupancy factors 1.0 through 1/40
- Number of patients N=80 to N=1 per week
- Protection Level: 1, 2, 2.5, 5, 7.5 and 10 mSv
- Administered activity: 20 mCi to 5 mCi
- Uptake time: 1.5 to 0.25 hours
- Distance from chair: 1.0 to 6.0 m

PET-Uptake Room Shielding – Factor comparison



PET-Uptake Room Shielding – Factor comparison



PET-Imaging Room Shielding – Factor comparison

- Apply "voiding" factor (0.85)
- Apply gantry attenuation factor (0.85)
- Applying 1 factor reduces shielding requirement by 17%
- Applying both factors reduces shielding requirement by 34%

For PET shielding, TG-108 recommends that shielding calculations be performed for F-18 because

1. F-18 is more readily available
2. F-18 has the highest energy photon emission
3. F-18 has a relatively long half-life in comparison to t other positron emitting isotopes
4. All other positron emitting isotopes have lower effective dose equivalent dose rate constants in tiss
5. None of the above

20% | 20% | 20% | 20% | 20%

10

Answer: C

F-18 has the longest half-life of commonly used PET isotopes. Shielding for this longer isotope would be appropriate.

Reference: Madsen, M., et. Al., AAPM Task Group 108: PET and PET/CT Shielding Requirements, Med. Phys. 33 (1) January 2006

The amount of annihilation radiation absorbed by the patient during a PET study is about

1. 74%
2. 64%
3. 100%
4. 36%
5. 24%

20% | 20% | 20% | 20% | 20%

10

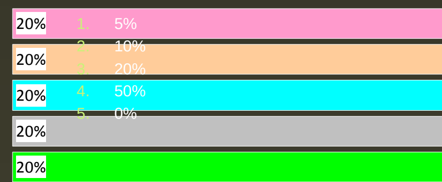
Answer: B

The patient absorbs about 36% of the annihilation radiation based on a number of papers that analyzed the exposure rates around patients injected with F-18

Reference: Madsen, M., et. Al., AAPM Task Group 108: PET and PET/CT Shielding Requirements, Med. Phys. 33 (1) January 2006

The PET gantry and detectors effectively reduce the dose rate by about

1. 5%
2. 10%
3. 20%
4. 50%
5. 0%



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Answer: C

Average of about 20% depends on gantry width, bed positions, etc. Effectively about 15% given the setup time where patient is outside the gantry

Reference: Madsen, M., et. Al., AAPM Task Group 108: PET and PET/CT Shielding Requirements, Med. Phys. 33 (1) January 2006

Radiation Protection Survey

- Evaluation of proper installation
  - During construction phase – prior to machine install
  - Protect contractor
  - Visual
  - G-M or scintillation detector with RAM
    - Need RAM license
    - May get "false positives"

Radiation Protection Survey

- Evaluate Shielding Adequacy
  - Ensure exposure levels are within regulatory limits
  - Include factors independent of shielding design
    - Number of patients
    - Occupancy factor
  - Typically exposure is to an AREA not an INDIVIDUAL = VERY CONSERVATIVE

Radiation Protection Survey

- Utilize the correct meter
  - Pressurized Ion Chamber
    - Integrate mode
    - Careful with exposure rate mode
    - Some energy dependence although negligible in the diagnostic scatter range
  - G-M meter NOT appropriate
    - VERY energy dependent

Radiation Protection Survey – Measure the Transmission

- Calculating exposure – Transmission Method
  - Integrated measurement outside room/integrated measurement inside room

$$x = \frac{1}{\alpha\gamma} ln\left(\frac{B^{-\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}}\right)$$

NCRP 147

  - Using appropriate tables and transmission data, can calculate total number of patients allowed
  - CAVEAT: many assumptions in calculation to determine dose/year

Radiation Protection Survey – Measuring Exposure Rate

- Calculating exposure – Measured exposure method
  - Exposure reading outside wall (mrem/hr)
    - CAUTION: response time (2-5 seconds)
  - Determine annual dose based on appropriate factors

$$\frac{mrem/hr}{3600\ s/hr} * \frac{1}{mA} * N * \frac{mAs}{pt} * T$$

Radiation Protection Survey – What about PET?

- Uptake room
  - F-18 injected into Jaszczak phantom

$$\frac{mrem/hr}{A} * N * A_0 * t_u * R_{t_u} * T * \text{Absorption factor}$$

Radiation Protection Survey – the proof is in the pudding

- Typical radiographic room
  - 160 patients/week
  - 150 mAs per patient (Table 4.3)

Area	Description	Occupancy	Reading in mR/hr	Dose per Year in mRem	Dose < Reg. Limit?
1	Control Area	1	0.07	0.5	Yes
2	Control Area Door	0.125	0.06	0.1	Yes
3	Corridor	0.2	0.05	0.1	Yes
4	Corridor Door	0.125	0.2	0.2	Yes
5	Restroom	0.05	0.22	0.1	Yes
6	B136 SPECTCT	0.5	0.05	0.2	Yes
7 - Below	Waiting Room Below	0.05	0.05	0.0	Yes
8 - Above	Exam Room Above	0.5	0.06	0.2	Yes

- Measured at 85 kVp

Radiation Protection Survey – the proof is in the pudding

- Typical radiographic room
  - 1000 patients/week
  - 150 mAs per patient (Table 4.3)

Survey Readings					
Area	Description	Occupancy	Reading in mR/hr	Dose per Year in mRem	Dose < Reg. Limit?
1	Control Area	1	0.07	3.0	Yes
2	Control Area Door	0.125	0.06	0.3	Yes
3	Corridor	0.2	0.05	0.4	Yes
4	Corridor Door	0.125	0.2	1.1	Yes
5	Restroom	0.05	0.22	0.5	Yes
6	B136 SPECTCT	0.5	0.05	1.1	Yes
7 - Below	Waiting Room Below	0.05	0.05	0.1	Yes
8 - Above	Exam Room Above	0.5	0.06	1.3	Yes

All of the following are factors for determining the adequacy of shielding by performing a radiation safety area survey EXCEPT:

1. Occupancy Factor
2. Measured dose rate
3. Workload (beam on time)
4. Survey Meter HV setting
5. Dose limit for area of survey

20%
20%
20%
20%
20%

10

Answer: D

The survey meter HV setting has little to do with ion chamber survey meter readings

Reference: Madsen, M., et. Al., AAPM Task Group 108: PET and PET/CT Shielding Requirements, Med. Phys. 33 (1) January 2006

Dollars

- Lead typically laminated in drywall
  - Thicknesses > 1/8 in plywood or > 1" stand alone – requires support
- Height to 7 ft unless shielding is required above
  - Most multi-floor facilities constructed with 4" light – weight concrete (published data for concrete = normal weight 147 lbs/ft^3)
- Concrete block may be considered
- Other shielding materials

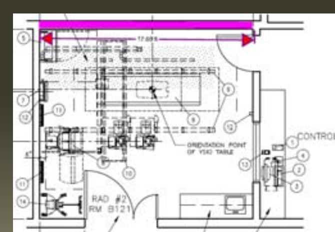
Cost of shielding

mmPB	Inch Equiv	Cost Range / Sq ft	Average Cost
0.7937	1/32	$10 - 14	$12
1.1906	3/64	$14-16	$15
1.5875	1/16	$20-23	$21
1.9844	5/64	$23-26	$24
2.3812	3/32	$26-29	$28
3.175	1/8	$32-36	$34
12.7	1/2	$100-110	$106
25.4	1	$140-160	$150
50.8	2	$250-300	$275
4" concrete		$60-70	$65
6" concrete		$80	$80

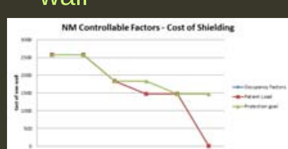
- Prices reflect INSTALLED price (non-union)
- Does not include freight/taxes

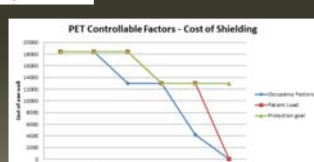
Typical room shielding cost – One wall

- One wall 20 ft long
- Ground floor
- No shielding above



Typical room shielding cost – One wall





Typical room shielding cost – comparisons

- All walls (assume square)
  - $7350
  - Take away one wall = $5513
- Occupied above
  - Wall shielding extended to 12 ft: Total cost $12,600 (71% increase)
  - What about shielding ceiling?
    - Additional lead cost
    - Increased structural support costs
    - Concrete between floors = lightweight concrete

Typical room shielding cost – comparisons

- Occupancy factor difference
  - T=1: $4,410
  - T=1/20: $2,520
  - T=1/40: $0
- 2 Walls affected
  - $5040 savings
  - 5,627 hospitals and 5,114 diagnostic imaging centers- $54,134,640

Summary

- RAM shielding workload heavily dependent on isotope, activity, and procedure type
- Area surveys are extremely important to determine exposure to staff and public but work needs to be done on accuracy
- “Adjustable” factors in shielding specification should be carefully considered and result in significant cost reductions