Radiation Shielding in a PET/CT Department: Use of Optimisation Techniques

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In a Positron Emission Tomography (PET) scanning centre, radionuclides with 511keV annihilation gammas (e.g. ^{18}F, ^{11}C, ^{13}N) are administered to patients for clinical imaging. In the department, multiple radiation sources in multiple locations are present at any one time i.e. mobile patients are located in uptake holding bays and scanner rooms throughout their patient journey through the department. The high dose rates from each source combined with the penetrating 511keV photons result in the requirement for substantial shielding to reduce staff doses to acceptable levels. For a new PET/CT department, this shielding can encompass a significant portion of the total project cost.

In this study, the shielding requirements were calculated for a new clinical PET Centre, with the aim of restricting radiation dose levels to within appropriate dose constraints and keep doses to As Low As Reasonably Practicable (ALARP). Radiation doses to staff and the public were calculated for a complex configuration of sources from the department plans. An iteration technique was then used to investigate the effect of changing barrier thickness on radiation doses to different staff groups and other persons, taking into account weighted occupancy factors in different locations. Optimisation of the shielding design was achieved by assessing compliance with the proposed dose constraints and by use of a Cost Benefit Analysis (CBA) model using calculated collective dose, associated detriment and shielding cost model.

Shielding Calculations

On the proposed new departmental plan, patient sources were identified, and critical dose positions selected (See Figure 1). The annual radiation dose to each critical dose point was then calculated from each ray path using the following assumptions:

- *Dose rate constant from ^{18}F = 0.188 μSv m²/(MBq hr) [1]*
- *All patients administered with 350MBq ^{18}F, followed by 90 minute uptake time and 30 minute scan time*
- *Patient attenuation factor of 0.36*
- *Dose rate from each patient post-injection at 2m D_0= 10.5 μSvhr^{-1}*
- *Workload of 12 patients/scanner/day*

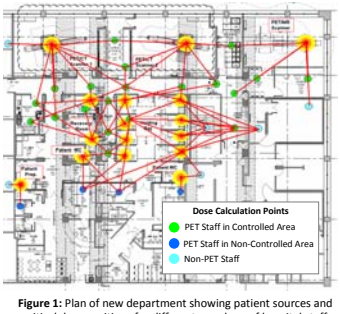

Figure 1: Plan of new department showing patient sources and critical dose positions for different members of hospital staff

For each barrier in the department, lead shielding of thickness (t) ranging from 2-30mm was selected. Taking the TVL of lead for 511keV broad beam transmission to be 17mm, the dose at each dose point was calculated with transmission through the lead barriers along each ray path using the formula:

$$Dose_p = \sum_{i=1}^{N} \frac{D_0}{R_i^2} \times e^{-\left(\frac{\ln 10}{TVL}\right)t}$$

A correction for oblique incidence was made by calculation of an effective ray path distance through each barrier. Barriers were increased in increments of a single HVL (5mm) systematically to provide a range of shielding configurations. Staff occupancy fractions were estimated for the critical points according to occupational role. Annual dose for each staff group was calculated for each shielding iteration. The collective dose in manSv for each shielding iteration was computed by adding the dose to all persons over 20 years of operation.

	Lead Thickness (mm): ITERATIONS						
Description	1	2	3	4	4b	5	6
Holding Bay	10	15	20	25	25	25	25
Holding Bay	10	10	15	20	20	20	25
Holding Bay	10	10	15	20	20	20	25
Holding Bay	10	15	20	25	25	25	25
Holding Bay Partitions (3 short)	5	10	15	20	25	25	25
Holding Bay Partitions (3 Long)	5	10	15	20	25	25	25
Back of Hot Lab	5	5	10	10	10	10	15
Recovery/Anaesthetic	5	5	10	10	10	15	15
Recovery/Anaesthetic	5	5	10	10	10	15	15
Recovery/Anaesthetic	5	5	10	10	10	15	15
Recovery/Anaesthetic	5	5	10	10	10	15	15
Recovery/Anaesthetic Partition	2.24	2.24	5	5	10	10	15
Patient WC	0	2.24	5	5	5	10	15
Patient WC	0	2.24	5	5	5	10	15
Patient Prep	0	2.24	5	5	5	5	10
Wall of Admin Office	0	0	0	5	5	10	10
Wall of Clinical Director	0	0	0	5	5	10	10
Wall of Scientists Room/P WC	10	15	20	25	25	25	30
Back Wall of Patient WC	5	10	15	20	20	20	25
Blood Lab	0	0	0	5	5	10	10
Blood Lab	0	0	0	5	5	10	10
Blood Lab	0	0	0	5	5	10	10
Scan Suite 1	2.24	5	10	10	10	10	15
Scan Suite 1	2.24	5	10	10	10	10	15
Scan Suite 1/Control Room	2.24	5	10	10	10	10	15
Scan Suite 2/Control Room	2.24	5	10	10	10	10	15
Scan Suite 2	2.24	5	10	10	10	10	15
Scan Suite 2	2.24	5	10	10	10	10	15
PET/MR	2.24	5	10	10	10	10	15

Table 1: Lead shielding in every barrier for each iteration

Optimisation

In radiation shielding specifications, the degree of shielding chosen is a trade-off between the level of radiation dose staff/public will receive from the proposed design, and the financial cost to install this shielding (cost of lead, installation, floor strengthening, etc.) The aim of optimisation is to find the right balance between radiation dose and shielding cost. The following factors /methods were used to assess proposed shielding design and find the optimised layout.

Radiation Dose Constraints

Radiation dose received by staff and members of the public must be ALARP and this is assessed using dose constraints. The dose constraints set for the relevant groups are shown in Table 2 below:

Table 2: Dose constraint levels for different staff and public groups

Staff Group	Annual Dose Constraint
PET Technologists/Radiographers	6mSv
PET Scientists/Consultants	1mSv
PET Admin Staff/Non PET Staff/Public	0.3mSv

Cost Benefit Analysis

To assess the level at which additional shielding no longer reduces doses significantly, Cost Benefit Analysis (CBA) can be used. This is a tool which enables quantification of optimisation to provide a measure by which a fair resource allocation to radiation protection be made. For total shielding cost X and health detriment cost Y, the total cost is expressed as Z = X + Y. The optimum situation will occur when X + Y is a minimum, as demonstrated in Figure 2.

For CBA, several reference values are required. The cost of lead (£/tonne) and cost of installation (£/tonne) was enquired from shielding suppliers. To quantify the health detriment, the collective dose (manSv) is multiplied by the monetary value of the manSv (£). This value is determined by economic factors (i.e. financial cost of loss of life expectancy), staff aversion to receiving high dose, and on a local level, what it has been deemed appropriate to pay in order to avert 1 manSv. IPEM Report 82 [2] gives the NRPB recommended value of the manSv for occupational exposure of £50,000 (1986). Factoring inflation in, this will equate to a current value of the manSv of ≈£120,000

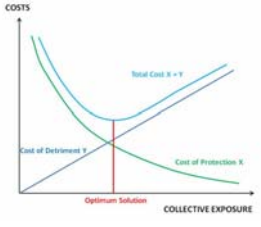

Figure 2: Principle of Cost Benefit Analysis [3]

Results

Table 3 and Figure 3 demonstrate the different radiation dose levels received by staff in the department for each shielding iteration. It was found that iteration 4b was the first iteration to meet all of the set dose constraints.

Dose Levels Colour Scale
6<= Dose <20 mSv/year
3 <= Dose <6 mSv/year
1<= Dose < 3 mSv/year
0.3 <= Dose < 1 mSv/year
Dose < 0.3 mSv/year

	Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 4b	Iteration 5	Iteration 6
Technologists	4.10	2.66	1.57	1.24	1.19	1.07	0.96
Technologists with Injections	7.10	5.66	4.57	4.24	4.19	4.07	3.96
MRI Staff	1.31	1.04	0.60	0.52	0.52	0.52	0.35
Scientists	4.63	2.50	1.49	1.49	0.92	0.88	0.78
Consultants	2.80	2.33	1.63	0.86	0.83	0.57	0.52
Admin Staff	0.78	0.78	0.78	0.28	0.28	0.11	0.09

Table 3: PET Staff annual doses for each iteration (6 Technologists; injection dose = 2 μSv/patient)

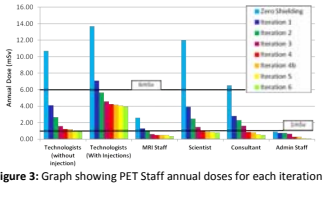

Figure 3: Graph showing PET Staff annual doses for each iteration

The Cost Benefit Analysis curve containing results from all iterations is shown in Figure 4 taking a value of £120,000/manSv. It can be seen that the CBA curve is optimised around iteration 2 - 3. However, these iterations do not meet the staff and public radiation dose constraints. In particular the technologists would be very close to the whole body dose level at which classification would be required. These levels would result in exceeding local dose investigation levels and could therefore be considered not to be ALARP. Therefore further CBA analysis was performed at different levels of £/manSv. These curves are shown in Figures 5 and 6for £180,000 and £240,000 per manSv.

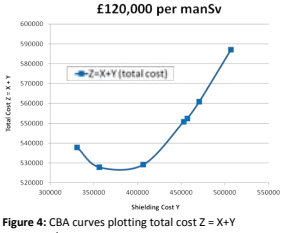

Figure 4: CBA curves plotting total cost Z = X+Y £/manSv = £120,000

It can be seen that detriment cost levels of £240,000 per manSv are consistent with an optimum solution of iteration 4b. At this level, all public and staff dose constraints would be met to ensure doses were ALARP and allow some degree of headroom on staff doses.

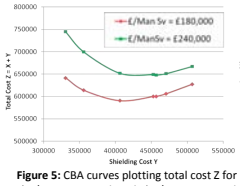

Figure 5: CBA curves plotting total cost Z for A) £/manSv = £180k and B) £/manSv = £240k

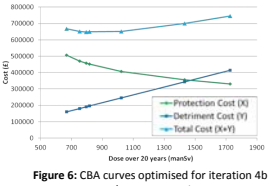

Figure 6: CBA curves optimised for iteration 4b £/manSv = £240k

Discussion and Conclusions

In the shielding design optimisation process, the staff and public doses determine at which level the shielding meets the minimum requirement. These doses can be reduced further to make ALARP by addition of extra shielding. However this may not be financially practicable. This is where Cost Benefit Analysis is a useful tool. However, it was found for this installation that dose constraints set tighter levels and higher protection than would be indicated by CBA under the more usual coefficient of £120k per manSv.

For dose constraints and costs to work together and indicate the same iterative solution (4b), a higher value of the manSv of £240,000 was required. There are additional factors for this installation which could justify the use of this greater manSv figure. These would include: (i) closeness to annual dose constraint, (ii) staff perception of proximity to a higher risk category, (iii) likelihood of staff requiring classification thereby greater administration costs, (iv) employment costs of more staff to reduce dose levels, and (v) staff turnover costs due to their occupational dose (especially the higher dose group of the technologists). In conclusion, Cost Benefit Analysis was found to be a useful tool in the optimisation of shielding in conjunction with dose constraints in an iterative design process. However, other factors that affect the appropriate figure for detriment cost per manSv must be taken into account.

References

1.AAPM Task Group 108: PET and PET/CT Shielding Requirements, Med Phys 33 (1) (Jan 2006)
2.Cost-Effective Methods of Patient Dose Reduction in Diagnostic Radiology; IPEM Report 82 (2001)
3.The Optimisation of Radiological Protection: Broadening the Process; ICRP Publication 101 (2006)

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