Australasian Physical & Engineering Sciences in Medicine (2019) 42:781–787
https://doi.org/10.1007/s13246-019-00782-1

SCIENTIFIC PAPER

Conservatism in linear accelerator bunker shielding

James Rijken[1,2] · Madhava Bhat[1] · Scott Crowe[2,3] · Jamie Trapp[2]

Received: 19 March 2019 / Accepted: 18 July 2019 / Published online: 25 July 2019

Abstract

Conservatism in the shielding of linear accelerator bunkers is engrained in the methodology of international protocols and guidelines. However, the degree to which this cautious and prudent approach is necessary should be judged against the International Committee of Radiation Protection's principles of exposure justification and optimisation. Radiation survey data from 75 concrete barriers was aggregated and compared to exposure predictions from three popular protocols in order to assess any conservatism in factors used to calculate scatter, leakage and beam penetration. These findings, in addition to a list of common conservative practices, were then used to tally the possible fiscal impact of an over-conservative approach to linear accelerator bunker shielding. While primary beam penetration was accurately predicted, stated conservatisms in scatter and leakage was found to be largely misplaced. An estimated total factor of conservatism calculated from a tally was found to be in agreement with literature values of radiotherapist occupational exposure. This factor amounted to a cost increase of 43% for a single bunker if all conservative assumptions were made. There are aspects of linear accelerator shielding design that have been shown to be overly conservative, beyond what is justifiable by the International Committee of Radiation Protection. Some adjustment to international protocol methodology may be required.

Keywords Shielding · Conservatism · NCRP 151 · Bunker · Linear accelerator

Introduction

The last 120 years has seen much change in the area of radiation protection. Initial recommendations had annual dose limits of around 700 mSv [5, 12] but this was reduced to 300 mSv in 1936, 150 mSv in 1948, 50 mSv in 1958 and finally the ICRP (International Committee of Radiation Protection) recommended an annual effective dose limit of 20 millisievert for radiation workers as part of their dose limit principle [10]. Nowadays, the subjective principle of ALARA (as low as reasonably achievable) is advised through an attitude of prudence [6] and the use of dose constraints [2, 10].

ICRP defines the fundamental principles of radiation protection as (1) justification, (2) optimisation and (3) dose limits [10]. Justification requires changes to the radiation exposure situation to cause more benefit than harm. This principle can be poorly applied in practice, focussing too much on radiation risk which results in over-conservatism. This conservative approach can then exceed the requirements of the radiation protection regulatory framework, demonstrated in the literature through occupational radiation exposure levels comparable to background levels [3, 6, 8, 25]. Hayton et al demonstrated that the 90th percentile annual dose for radiotherapists is only 0.28 mSv with 100% of workers in radiotherapy having neutron doses < 0.2 mSv/year [8]. The costs required to produce these occupational exposures may not be in agreement with the ICRP principles of justification [6] and optimisation which states that radiation exposure should be kept as low as reasonably achievable taking into account *economic* and societal factors.

Dose limits are another area of scrutiny [7, 22, 23] but this study will focus on the state of radiation protection in the field of radiotherapy with respect to the principles of justification and optimisation only. In any case, radiation exposure is better discussed within in framework of dose constraints for controlled exposure situations [2, 10]. To limit the radiation exposure to members of the public and radiation workers in accordance with international bodies

✉ James Rijken
james.rijken@genesiscare.com

1 GenesisCare, St Andrew's Hospital, Adelaide, SA, Australia

2 Queensland University of Technology, Brisbane, QLD, Australia

3 Royal Brisbane and Women's Hospital, Brisbane, QLD, Australia

and local regulations, an x ray source should be shielded. Modern shielding protocols provide methodology for the design and construction of shielding for high energy therapeutic x ray facilities. The protocols considered in this study are NCRP 151 [19], IAEA SRS 47 [9] and IPEM 75 [13, 14].

Conservatisms, which are simply assumptions and recommendations that include deliberate overestimations to ensure that radiation exposure is well below some level, are built into the shielding calculations of these protocols. This is necessary not only to meet the lower departmental dose constraints, *P*, but also to account for variables that may not be well quantified such as occupancy and work load. Unfortunately, it is unclear to what degree conservatism in barrier thickness calculations is justified and current linac shielding protocols may not be well aligned with ICRP's principles of optimisation and justification. This study has aimed to address this through a review of survey data, tallying costs of conservatism and providing recommendations.

Materials and methods

Data was accrued from radiation survey measurements of 14 Elekta linac bunkers varying in shape and design. The 75 barriers that were considered were ones that corresponded with the simplified linac bunker design shown in Fig. 1. These were split into three groups composed of (1) primary barriers, (2) secondary barriers on primary walls (referred to as A and B secondary barriers) as well as the roof, and (3) secondary barriers on the gun (G) and target (T) sides. Survey measurements were taken for the flattened 10 MV beam according to the methods described in NCRP 151 [19] using a variety of calibrated large-volume ion chamber survey meters with background doses subtracted. Readings were all corrected to a distance of $d = 6$ m from the isocentre.

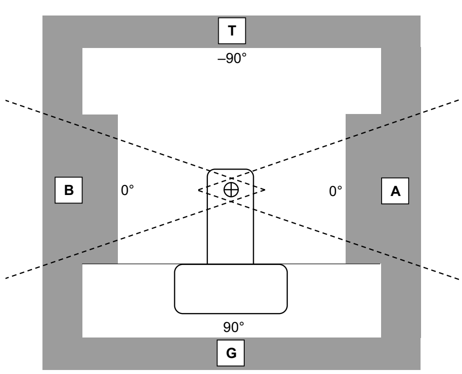

Fig. 1 Simplified linac bunker design used as a template to compare like barriers between linacs and to shielding protocol predictions. *G* gun side, *T* target side, *B* left, *A* right. A bunker maze or direct access door would usually present on the T side barrier or on the A or B side secondary barriers beyond the primary barrier

Survey meter data was compared to the predicted values at $d = 6$ m from NCRP 151 [19], IAEA SRS 47 [9] and IPEM 75 (1997) [13] through use of their tabulated TVLs and scatter fractions. The predicted dose rate after *n* TVLs was calculated according to the following equations for (1) primary beam, (2) leakage, and (3) patient scatter:

$$\dot{D}(\mathrm{TVL}_n)_{\mathrm{primary}} = \frac{\dot{D}(0)}{(1+d)^2} \times 10^{-n} \tag{1}$$

$$\dot{D}(\mathrm{TVL}_n)_{\mathrm{leakage}} = \frac{\dot{D}(0) \times 0.001}{(d)^2} \times 10^{-n} \tag{2}$$

$$\dot{D}(\mathrm{TVL}_n)_{\mathrm{scatter}} = \frac{\dot{D}(0) \times 4a}{(d)^2} \times 10^{-n} \tag{3}$$

where $\dot{D}(0)$ is the dose rate at isocentre which was taken as 6.6 Gy/minute for the 10 MV field with a field size of 40×40 cm^2 field, *a* is the patient scatter fraction and 0.001 represents the maximum allowable leakage of leakage rate of 0.1% [11]. For secondary barriers, both scatter and leakage were calculated and combined. For A and B side secondary barriers, a conservative assumption of 30° was taken for patient scattered radiation. A 90° scatter angle was utilised for G and T side barriers. Data was sourced from each protocol according to Table 1. Correlation was assessed using the Pearson correlation coefficient [21].

The monetary cost of findings from the survey data as well as common conservative assumptions was tallied through calculation of extra concrete required. This is similar to the method demonstrated by Coates where factors of conservatism were tallied for clearance of radioactive materials [6]. Of course, this is an estimate as it does not take into account some site specific construction costs. A 2.35 g/cm^3 grade concrete cost of $3000 AUD per cubic metre, which includes the cost of form work and labour, was used and is accurate for Australia as of 2019 (more complicated formwork will cost extra). The theoretical bunker considered had a ceiling height of 3 m and internal dimensions of 7 m by 7

Table 1 Location of data sourced to produce IDR comparisons for each shielding protocol

Parameter	NCRP 151 [19]	IAEA SRS 47 [9]	IPEM 75 [13]
Primary beam TVLs	Table B.2	Table 4	Figure 5.2 [14]
Scatter TVLs	Table B5.5a	Table 11	NA
Scatter fractions	Table B.4	Table 5 (at 1.5 cm)	NA
Leakage TVLs	Table B.7	Table 4	Figure 5.4 [14]

m (smaller and bigger bunkers were also considered). Initial primary and secondary barriers had thickness of 2 m and 1 m, respectively.

While assumptions such as the lack of patient attenuation, choice of use factor and occupancy factor, leakage rate, differences in leakage TVLs, and scattering field size are explicitly recommended in, or built into, the methodology of international shielding protocols, practices such as artificially increasing or rounding up barrier thicknesses and workloads as well as halving dose constraints are not dictated but have been observed anecdotally. In either case, the impact of such conservative practices, mandated or otherwise, can be quantified in a fiscal sense.

The exact dose constraints a department should choose are not formally prescribed by ICRP, nor by ARPANSA [2, 10], so long as the rule of ALARA is upheld given consideration of societal and *economic* factors. States and territories in Australia vary in their implementation of this principle with values between 5 and 20 mSv/year recommended for controlled areas. For the purpose of this investigation, a dose constraint, P, of 10 mSv/year has been assumed for controlled areas as a compromise and 0.5 mSv/year has been used for uncontrolled areas. Standardisation of dose constraints among regulatory bodies within Australia is certainly a discussion that should be had but falls outside the scope of this study.

Results

Both leakage and patient scatter contribute to secondary barrier survey measurements. The fraction of signal that is leakage, as predicted by NCRP [19] and IAEA [9], depends on TVL and scatter fraction values as well as barrier thickness. This is shown in Fig. 2. A large difference exists between the two popular protocols for both A/B and G/T secondary barriers. Leakage nearly accounts for all signal at G/T barriers while for A and B sides it may account for as much as a third of the total signal. Data for the plots was sourced as per Table 1.

Measured primary barrier instantaneous dose rates (IDRs) for different barrier thicknesses are shown in Fig. 3. These were found to have a strong correlation with predicted values from NCRP 151 [19] ($r = 0.995$), IAEA SRS 47 [9] ($r = 0.995$) and IPEM 75 (1997) [13] ($r = 0.995$).

Measured secondary barrier IDRs for A and B sides for different barrier thicknesses are shown in Fig. 4. The measured data correlated well with NCRP 151 ($r = 0.933$) and IAEA ($r = 0.940$) though not as tightly as for the primary beams. IPEM 75 (1997) was omitted due to it only considering leakage for secondary barrier calculations.

Gun side readings were found to be on average less than for the target side and neither could be represented

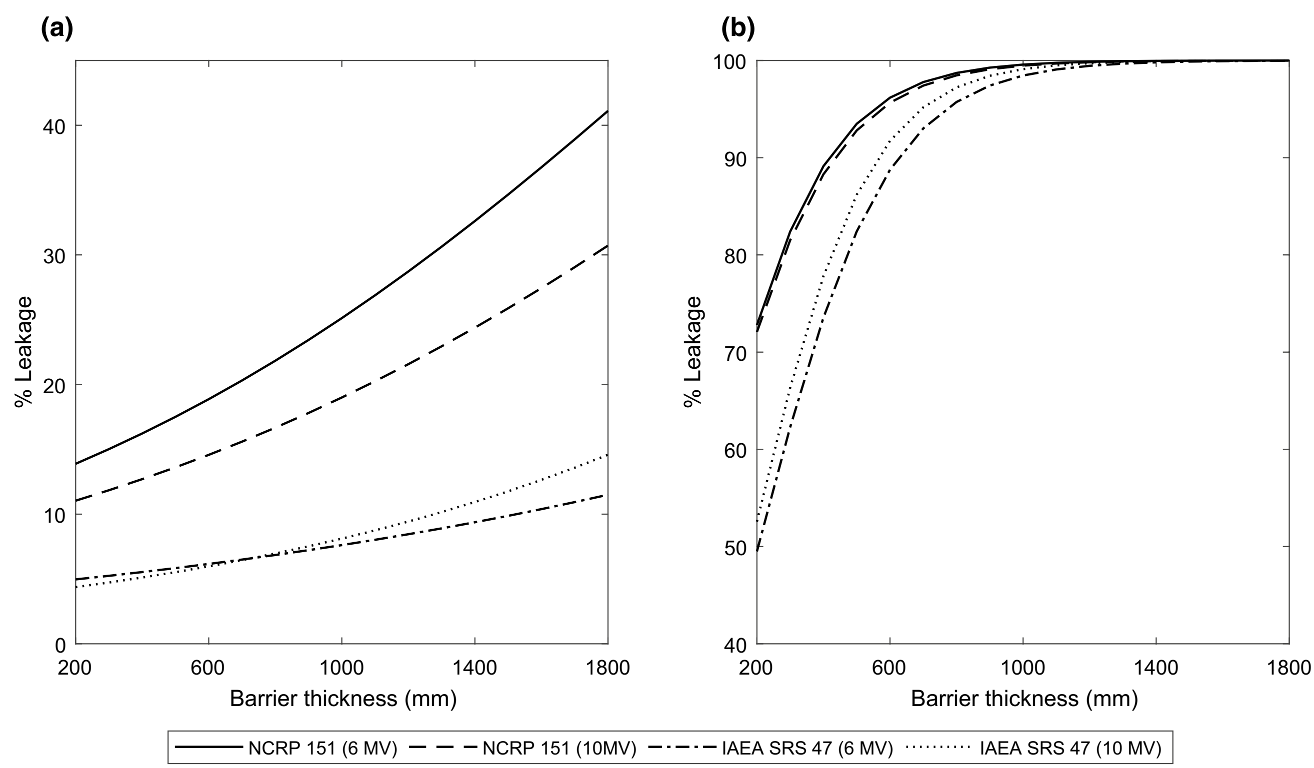

Fig. 2 Fraction of radiation survey signal contributed to by leakage for (**a**) A and B side secondary barriers (30°) and (**b**) G and T side secondary barriers (90°) as predicted by NCRP 151 [19] and IAEA SRS 47 [9] as a function of barrier thickness (ordinary concrete)

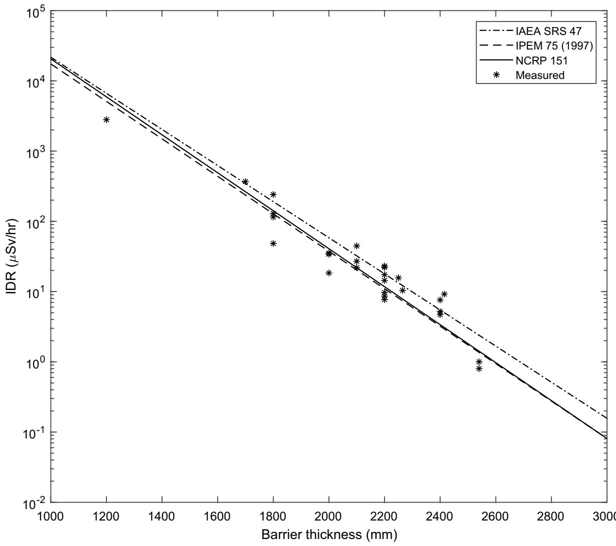

Fig. 3 Measured dose rates from primary barriers ($n = 27$) normalised to $d = 6$ m compared to predicted dose rates from NCRP 151 [19], IAEA SRS 47 [9] and IPEM 75 (1997) [13]

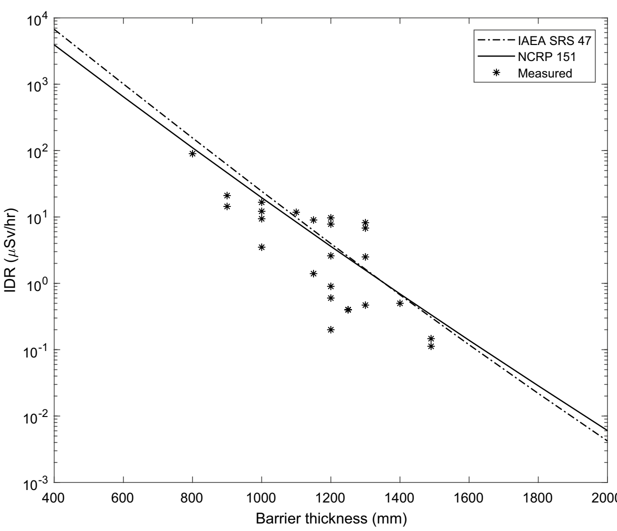

Fig. 4 Measured dose rates from secondary A and B side barriers ($n = 25$) normalised to $d = 6$ m compared to predicted dose rates from NCRP 151 [19] and IAEA SRS 47 [9]

by a trendline predicted from NCRP ($r = 0.695$), IAEA ($r = 0.776$) or IEPM ($r = 0.692$), demonstrating only weak correlation between the measured and predicted values. While all predicted values were higher than measured, IAEA was less conservative than the other two protocols. This is shown in Fig. 5.

The estimated resultant increases in HVLs required for a list of conservative assumptions and decisions is shown in Table 2. In the case where all assumptions or conservative decisions listed are made, the cumulative factors of

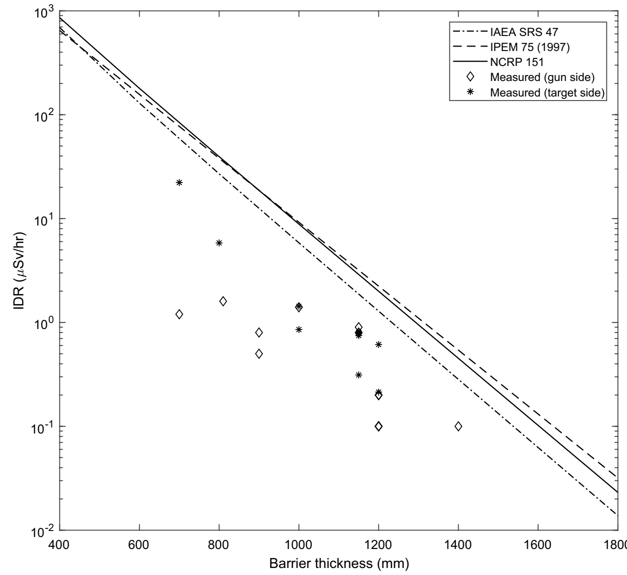

Fig. 5 Measured dose rates from gun side ($n = 13$) and target side ($n = 10$) secondary barriers normalised to $d = 6$ m compared to predicted dose rates from NCRP 151 [19], IAEA SRS 47 [9] and IPEM 75 (1997) [13]

conservatism were at least 45 (> 5.5 HVLs) for primary barriers, 23 (> 4.5 HVLs) for secondary A and B and 64 (> 6 HVLs) for secondary G and T. For an initial concrete volume of 237 m^3 for the bunker dimensions listed above, the volume is increased almost 43% due to over-conservatism when all assumptions are made, which is a total cost in excess of $300,000 AUD. Bunkers with internal dimensions of 6×6 m^2 and 8×8 m^2 had figures which were on average 14% less and 14% more, respectively, but still overall a relative cost increase of 43% for both.

Discussion

The fraction of exposure due to leakage measured at secondary barriers varies between NCRP 151 [19] and IAEA SRS 47 [9] (Fig. 2). In IAEA SRS 47, leakage TVLs are based on calculations by Nelson and LaRiviere [20] whereas NCRP derives their values from extrapolation and interpolation of data from older publications [1, 18]. A recent study by Kairn et al showed that, for A and B side secondary barriers, leakage only comprised around 5% of the survey meter signal [15] which is in agreement with the data from IAEA [9] in Fig. 2a. Kairn's measurement of leakage for gun/target side barriers (being around 100%) is consistent with both protocols. Since the scatter fractions between the two protocols are the same, NCRP's leakage TVLs are found to be grossly conservative.

Variations among protocols were not expected for primary barrier calculations due to the TVLs all being based

Table 2 The extra costs produced from conservative assumptions for a single linac bunker with internal dimensions of 7 × 7 m^2

Parameter	Assumption/decision	Thickness increase	Barrier	Volume (m^3)	Cost
Barrier thickness	Rounding up 10%	> 1 HVL	All	23.7	$71,000
P	Halving	1 HVL	All	18.2	$54,450
W	+50%	0.5 HVL	All	9.1	$27,225
U	Overestimation by double	1 HVL	Primary	7.2	$21,600
T	Overestimation by double	1 HVL	All	18.2	$54,450
Scatter field size	Double	1 HVL	Secondary A, B, roof	6.8	$20,250
Primary calculations	Lack of patient attenuation	1 HVL	Primary	7.2	$21,600
Leakage rate	Overestimation by double	1 HVL	Secondary G and T	4.2	$12,600
Leakage TVLs (NCRP or IAEA)	17% diff per TVL	1.5 HVLs	Secondary G and T	6.3	$18,900

on calculations by Nelson and LaRiviere [20]. Measured dose rates from radiation surveys for the primary barriers were well correlated with predictions from IAEA, NCRP and IPEM which demonstrates that the TVLs used in these protocols are accurate and cannot be considered to be conservative. Instead, conservatism in primary barriers comes from choice of *W*, *U*, *T*, *P*, the 40 × 40 field and the lack of patient attenuation. IPEM's shielding report from 1997 [13] opted for a single TVL like IAEA [9] but their latest edition [14] now recommends the use of an initial TVL then an equilibrium TVL thereafter in agreement with NCRP [19]. The choice of a single TVL or otherwise made little impact and all three protocols could be safely used for primary barrier calculations.

Measured dose rates for A and B side secondary barriers also were well correlated with protocol calculations (Fig. 4) and both IAEA [9] and NCRP [19] were comparable to each other. However, IAEA and NCRP both state that their small angle scatter fractions and scatter radiation TVLs are conservatively high, which disagrees with the measured data. This is coupled with the fact that the calculated IDRs utilised a conservatively small scattering angle of 30 degrees when in reality, many of the measured values had angles of 45 degrees or larger. So it was expected that the calculated values would be conservatively high for multiple reasons. This may be due to scatter fractions being based in Monte Carlo studies [24] rather than large amounts of survey data from clinical linacs and bunkers. From Fig. 2a and Kairn et al [15] we know that leakage has minimal contribution in this case, so the false assumptions of conservatism then lies with the scatter fractions and scatter radiation TVLs.

The deviations, then, between measured and calculated dose rates for target and gun side secondary barriers (Fig. 5) are in contrast to the agreement seen for the other barriers. Theoretical calculations only show weak correlation to measured data and IAEA's [9] differs notably from both NCRP [19] and IPEM [13]. This is the same difference seen in Fig. 2a due to the smaller TVLs recommended by IAEA for leakage which we know are accurate from corroboration by Kairn et al [15]. Therefore, the differences seen in Fig. 5 must be due to the assumption of a conservatively large leakage rate of 0.1% [11]. The leakage is also anisotropic as shown by the lower measured values on the gun side. Anisotropy can most likely be attributed to attenuation of leakage by the linac gantry itself, which is greater on the gun side of the room. Halving the leakage rate to 0.05% and using the more accurate TVLs from IAEA would still be a reasonably conservative approach to shielding these barriers, especially the gun side. If FFF modalities are used instead of flattened then the leakage rate might be further reduced [14, 16, 17].

The Australian Radiation Protection and Nuclear Safety Agency has shown that the highest occupational exposure radiotherapists receive is 0.28 mSv annually as recorded by their personal radiation monitoring badges [8]. This implies a factor of at least 71 lower than accepted dose limits and at least 36 when compared to dose constraints [2, 10]. The possible over-conservatism in barrier calculations by at least 5 HVLs (Table 2, factor of 23–64) therefore is in agreement with observed exposure monitoring data. This is comparable to the conservative factor of at least 100 calculated for assumptions made in the clearance of radioactive material [6]. An initial hypothesis for the low radiation exposure of radiotherapists was attributed mostly to overly optimistic workloads and the use of much smaller fields than allowed for in the shielding design. However, even overestimating the workload by 50% only requires an extra half a HVL and in conjunction with using smaller field sizes would only result in, at most, an over-conservatism factor of 4. So it is obvious then that some combination of the listed assumptions and decisions (Table 2) are being made to greater or lesser extents in order to produce the conservatism seen in occupational exposures [8].

Table 2 shows that conservative assumptions and decisions could lead to significant cost increases of up to an estimated 43%. This does not agree well with the radiation protection principles of justification and optimisation considering economic factors [10]. Coates had a similar conclusion that there was "absolutely no justification" for such levels of conservatism based on his findings concerning clearance levels [6]. The tabulated items are common approaches to conservatism either appearing in protocols [19] or in departments and do not include several other less easily quantifiable conservatisms associated with: IMRT factors, beam obliquity [4], use of lower energy modalities and calculation of roof thickness for greenfield sites based on skyshine alone. The final figure also does not include the extra ongoing savings possible through lower rent of a smaller footprint site, so the figure quoted it is quite likely to be an underestimate.

Of course, factoring in some conservatism has many benefits and is quite necessary to accommodate potential changes in the practice and to mitigate issues with the build etc. However, the need for a conservatism factor of at least 5 HVLs (or even a factor of at least 36–71 [8] as is currently shown by ARPANSA) requires more justification. Since there are several remaining conservatisms unaccounted for, the choice of just one listed conservatism (such as a reduced design goal/dose constraint) and making more accurate and informed decisions regarding the rest will still produce a conservative bunker adhering to ICRP 103 [10] and regulatory requirements. One limitation identified is that this does not take into account jurisdictions that have regulatory requirements for maximum instantaneous dose rates which would be the major factor in determining barrier thickness.

In general, apart from practices such as rounding and choice of workload, departing from the listed over-conservative assumptions and decisions would mean moving away from current shielding protocols which this study acknowledges may be difficult for a radiation safety officer. In addition, one may still expect local issues where the responsible person has views differing from those of the regulators or third party contractors. Nonetheless, this study has shown that a safe practice can be responsibly and honestly upheld in accordance with the principles of ICRP while still making notable savings by better quantification of assumptions. Furthermore, it has been demonstrated that the current shielding protocols require some adjustment in order to align better with the principles of the ICRP.

Conclusion

A study into the level of conservatism in major linac bunker shielding protocols was conducted through an analysis of survey data and current radiation worker exposure levels in order to quantify possible over-shielding factors. The results of this study suggest that the level of conservatism differs among NCRP 151, IAEA SRS 47 and IPEM 75 and in general is either overstated or unreasonably large. This can lead to suboptimal shielding of radiotherapy bunkers with respect to ICRP dose constraints when multiple conservative assumptions are made. In turn, this leads to an unnecessary cost increase for new builds which is in disagreement with the ICRP principles of justification and optimisation. The impact of too many conservative assumptions should be considered for new linac bunker builds.

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

References

1. Abrath FG, Bello J, Purdy JA (1983) Attenuation of primary and scatter radiation in concrete and steel for 18 MV x-rays from a clinac-20 linear accelerator. Health Phys 45(5):969–973
2. ARPANSA (2016) Radiation protection in planned exposure situations. Radiation protection series C-1. Australian Radiation Protection and Nuclear Safety Agency, Miranda
3. Bhat M (2010) Fear of radiation is frightening. Aust Phys Eng Sci Med 33(3):215–217
4. Biggs PJ (1996) Obliquity factors for 60 co and 4, 10, and 18 MV x rays for concrete, steel, and lead and angles of incidence between 0 and 70 degrees. Health Phys 70(4):527–536
5. Brodsky A, Kathren R (1989) Historical development of radiation safety practices in radiology. Radiographics 9(6):1267–1275
6. Coates R (2017) Prudence and conservatism in radiation protection: a case study. Radiat Prot Dosim 173(1–3):100–103
7. Feinendegen LE (2016) Quantification of adaptive protection following low-dose irradiation. Health Phys 110(3):276–280
8. Hayton A, Litwin M (2019) O83 occupational radiation doses in medical professions—a review of 30 years of data from the ARPANSA PRMS database. Aust Phys Eng Sci Med 42(1):285–401
9. IAEA (2006) Safety report series no. 47, radiation protection in the design of radiotherapy facilities. International Atomic Energy Agency, Vienna
10. ICRP (2007) The 2007 recommendations of the international commission on radiological protection. ICRP publication 103. ann. ICRP 37(2–4). International Commission on Radiological Protection, Ottawa
11. IEC (2009) Medical electrical equipment–part 2-1: particular requirements for the safety of electron accelerators in the range 1 MeV to 50 MeV 60601-2-1, 2nd edn. International Electrotechnical Commission, Geneva
12. Inkret WC, Meinhold CB, Taschner JC (1995) Protection standards. Los Alamos Sci 25:117–123
13. IPEM (1997) Design and shielding of radiotherapy treatment facilities. IPEM report 75. Institute of Physics and Engineering in Medicine, New York
14. IPEM (2017) Design and shielding of radiotherapy treatment facilities. IPEM report 75, 2nd edn. Institute of Physics and Engineering in Medicine, New York
15. Kairn T, Crowe S, Trapp J (2013) Correcting radiation survey data to account for increased leakage during intensity modulated radiotherapy treatments. Med Phys. https://doi.org/10.1118/1.4823776

16. Kragl G, Baier F, Lutz S, Albrich D, Dalaryd M, Kroupa B, Wiezorek T, Knöös T, Georg D (2011) Flattening filter free beams in SBRT and IMRT: dosimetric assessment of peripheral doses. Zeitschrift für Medizinische Physik 21(2):91–101
17. Kry SF, Howell RM, Polf J, Mohan R, Vassiliev ON (2009) Treatment vault shielding for a flattening filter-free medical linear accelerator. Phys Med Biol 54(5):1265
18. NCRP (1976) Structural shielding design and evaluation for medical use of x-rays and gamma-rays of energies up to 10 MeV, rep. 49. National Council on Radiation Protection and Measurements, Washington
19. NCRP (2005) Structural shielding design and evaluation for megavoltage x-and gamma-ray radiotherapy facilities: Recommendations of the national council on radiation protection and measurements. National Council on Radiation Protection and Measurements, Bethesda
20. Nelson WR, LaRiviere P (1983) Primary and leakage radiation calculations at 6-MeV, 10-MeV and 25-MeV. Health Phys 47(SLAC–PUB–3039):811
21. Pearson K (1895) Note on regression and inheritance in the case of two parents. Proc R Soc Lond 58:240–242
22. Pollycove M, Feinendegen LE (2003) Radiation-induced versus endogenous dna damage: possible effect of inducible protective responses in mitigating endogenous damage. Human Exp Toxicol 22(6):290–306
23. Rattan SI, Kyriazi M (2018) The science of hormesis in health and longevity. Academic Press, Cambridge
24. Taylor PL, Rodgers JE, Shobe J (1999) Scatter fractions from linear accelerators with x-ray energies from 6 to 24 MV. Med Phys 26(8):1442–1446
25. Yoshimoto K, Furuta H, Inoue K, Fukushi M, Kasagi F et al (2018) Occupational radiation exposure and leukemia mortality among nuclear workers in Japan: J-EPISODE, 1991–2010. Jpn J Health Phys 53(3):146–153