Kotre, John ORCID: https://orcid.org/0000-0002-1890-1160 (2022) Application of ALARP cost-benefit analysis to hospital-based radiation protection. Journal of Radiological Protection, 42 (4). 041509.

Downloaded from: http://insight.cumbria.ac.uk/id/eprint/6728/

Usage of any items from the University of Cumbria's institutional repository 'Insight' must conform to the following fair usage guidelines.

Any item and its associated metadata held in the University of Cumbria's institutional repository Insight (unless stated otherwise on the metadata record) may be copied, displayed or performed, and stored in line with the JISC fair dealing guidelines (available here) for educational and not-for-profit activities

provided that

- the authors, title and full bibliographic details of the item are cited clearly when any part of the work is referred to verbally or in the written form
- a hyperlink/URL to the original Insight record of that item is included in any citations of the work
- the content is not changed in any way
- all files required for usage of the item are kept together with the main item file.

You may not

- sell any part of an item
- refer to any part of an item without citation
- amend any item or contextualise it in a way that will impugn the creator's reputation
- remove or alter the copyright statement on an item.

The full policy can be found here.
Alternatively contact the University of Cumbria Repository Editor by emailing insight@cumbria.ac.uk.

Application of ALARP cost-benefit analysis to hospital-based radiation protection

Short title: ALARP in hospital radiation protection

Full paper

C J Kotre Ph.D FBIR
Visiting Research Fellow
Institute of Health
University of Cumbria
Bowerham Road
Lancaster
LA1 3JD
UK

john.kotre@cumbria.ac.uk

Application of ALARP cost-benefit analysis to hospital-based radiation protection

ABSTRACT

The UK Ionising Radiations Regulations 2017 require employers to restrict radiation doses to their employees and the public to be As Low As Reasonably Practicable (ALARP). This article looks at the boundary between what might be considered to be reasonable and unreasonable in protecting staff and the general public in the field of hospital-based diagnostic radiology. Guidance on cost-benefit analysis in support of ALARP has been used to formulate relationships for the estimation of the cost at which a radiation protection intervention is no longer ALARP. These relationships allow for a direct link between a reduction in radiation exposure and the maximum reasonable ALARP cost of intervention. Application of the approach to hospital-based radiation protection situations show that the ALARP cost limits for protecting radiation workers against the residual risks in the hospital environment are relatively low. Conversely, the ALARP limit to investment in public dose reduction by means of reducing patient doses can be very high.

Introduction

Under Regulation 9(1) of the Ionising Radiations Regulations 2017 [1], ‘every employer must, in relation to any work with ionising radiation that it undertakes, take all necessary steps to restrict as far as is reasonably practicable the extent to which its employees and other persons are exposed to ionising radiation.’ This is normally expressed as the duty to make staff and public radiation doses As Low As Reasonably Practicable (ALARP). This wording implies that some potential actions of the employer to lower radiation doses may not be reasonably practicable, and therefore that the employer is relieved of the legal requirement to take such unreasonable actions. This paper looks at the boundary between what might be considered to be reasonable and unreasonable in protecting staff and the general public in the field of hospital-based diagnostic radiology.

Many of the regulations protecting UK employees derive from the Health and Safety at Work Regulations of 1974 [2]. Although these regulations place some absolute duties on the employer, other duties are qualified by expressions such as ‘so far as is reasonably practicable’ (SFAIRP), ‘as low as reasonably achievable’ (ALARA), and ‘as low as reasonably practicable’ (ALARP) in order to avoid the imposition of duties that no-one can fulfil [3]. These terms are substantially interchangeable [4] and the question arises as to the meaning of ‘reasonably practicable’. The most significant and commonly cited case is that of Edwards v. National Coal Board (1949) [5], the judgment on which included the requirement that there should be a ‘gross disproportion’ between the cost of a safety intervention and the potential cost of failure to act. This gross disproportion factor acts to encourage a risk-averse approach to the implementation of safety measures.

Cost of a radiation-induced late fatality

The UK Health and Safety Executive (HSE) provide periodic advice on the monetary value of an attributable fatality for the purposes of cost-benefit analyses of potential safety measures. As this value changes with time, it will be assigned the symbol V_F in the discussions below. (At the time of writing, V_F has the value of £1,296,000 as the human cost plus £449,100 as the cost to society, so a total of £1,745,100 [6]). In the field of radiation protection of workers and the general public in hospitals (not nuclear accidents), any resulting fatality would be due to cancer. Due to the perceived public intolerance of a death due to cancer, another HSE document recommends that the value of a death by cancer should be multiplied by 2 compared with that of a conventional accidental death [3][7]. Research by HSE [8] concludes that this factor of 2 may be too high, but no updated value has yet been advised, so the factor of 2 is retained here. A still further HSE document on the public tolerability of risk from nuclear power stations [9] notes that for late deaths due to exposure to ionising radiation, the attributable death is unlikely to occur until ages in the region of 60 to 80 years. This implies that the impact of the death is less than that of an immediate death in an industrial accident, and it is argued that an appropriate correction is the life lost due to a late death, approximately 15 years, divided by the years lost for an immediate death, typically 35 years. The suggested correction factor is 0.43. The cost of a radiation-induced late fatality for the purposes of cost-benefit analysis therefore becomes:

$$C_F = 0.86\ V_F \tag{1}$$

Where: C_F is the cost of a radiation-induced late fatality
V_F is the current monetary value of an attributable fatality

Gross Disproportion Factor

Interventions carried out by the employer or operator to reduce the risk from ionising radiation to employees or the general public will normally involve a cost. Such an intervention will also bring about a benefit in terms of lives saved (or fractional probabilities of lives saved) which can be expressed in monetary terms. The ratio of the costs to the benefits can be used to judge the value of the proposed intervention. If this ratio becomes greater than some defined value, then the cost can be said to be 'grossly disproportionate' to the benefits and the proposed intervention would be not 'reasonably practicable'. The gross disproportion factor therefore defines the boundary between an intervention that is ALARP, and required by regulation to be implemented, and an intervention which is unreasonable and which the employer or operator has no legal requirement to proceed with.

In this section a quantitative relationship between the annual individual risk of fatality and the ALARP gross disproportion factor will be suggested. At the outset it must be emphasized that there is no firm guidance on actual values for the gross disproportion factor because it is essentially a matter defined by legal decisions arising from court cases. A range of published views exist, however, against which the relationships suggested here can be tested for consistency.

The HSE framework for the tolerability of risk is based on the existence of a level of risk above which the risk is considered to be intolerable, and a much lower level of risk below which risks are considered to be broadly acceptable. Between these two levels the risks are considered to be tolerable if ALARP [3]. The HSE give the value of intolerable annual risk of fatality for workers as 10^{-3}, for the general public 10^{-4}, and the lower broadly acceptable annual risk is given as 10^{-6} [9, 10]. In HSE guidance [10], the basic principle of a disproportion factor rising between 1 at the broadly acceptable boundary to a suggested value of 10 at the intolerable boundary is outlined although it is stressed that the way the gross disproportion factor changes with risk is still unclear. A number of suggestions for specific values of gross disproportion factor have been made, and it is important to note that since the intolerable boundary for the general public and workers lie at different levels of risk, there are two different relationships to be derived.

For the general public, Bowles [11] suggests a relationship rising linearly from a value of 3 at the broadly acceptable boundary to 10 at the intolerable boundary against a logarithmic scale of risk. This is not inconsistent with the values of 2 and 10 for low and high risks to the general public quoted in the HSE submission to the Sizewell B enquiry [12]. A lower value of 1 for individual risks is contained within the range of factors quoted by the HSE in Annex 1 of reference 10. These data also show that the gross disproportion factor increases with number of fatalities arising from an incident, and this emphasizes that it should be the individual risk used in this work, with the risk resulting in a statistical fraction of a fatality. Earlier work by the then UK National Radiological Protection Board (NRPB) attempted to quantify the increasing level of individual radiation risk aversion as a multiplier to the baseline detriment cost [13] which also has the effect of a disproportion factor. This factor is expressed as a band of values on a logarithmic scale of annual individual dose and can be converted to risk of fatality for the purposes of comparison using the ICRP radiation fatal risk factor of 0.05 per Sv [14]. The ICRP conversion factor for approximated overall fatal cancer risk has been used (rather than detriment-adjusted risk coefficients) to make a direct link to the broadly acceptable and intolerable boundaries which are set in terms of annual risk of fatality.

Figure 1 illustrates these various references together with the relationship suggested here, which is a gross disproportion factor with value 1 at the broadly acceptable level of 10^{-6} fatalities per year for the general public, rising to 10 at the intolerability boundary of 10^{-4} fatalities per year on a logarithmic scale of risk.

$$D_P = 4.5 \log_{10}(F) + 28 \qquad (2)$$

Where: D_P is the ALARP gross disproportion factor for the general public
F is the annual individual risk of fatality where $10^{-6} < F < 10^{-4}$

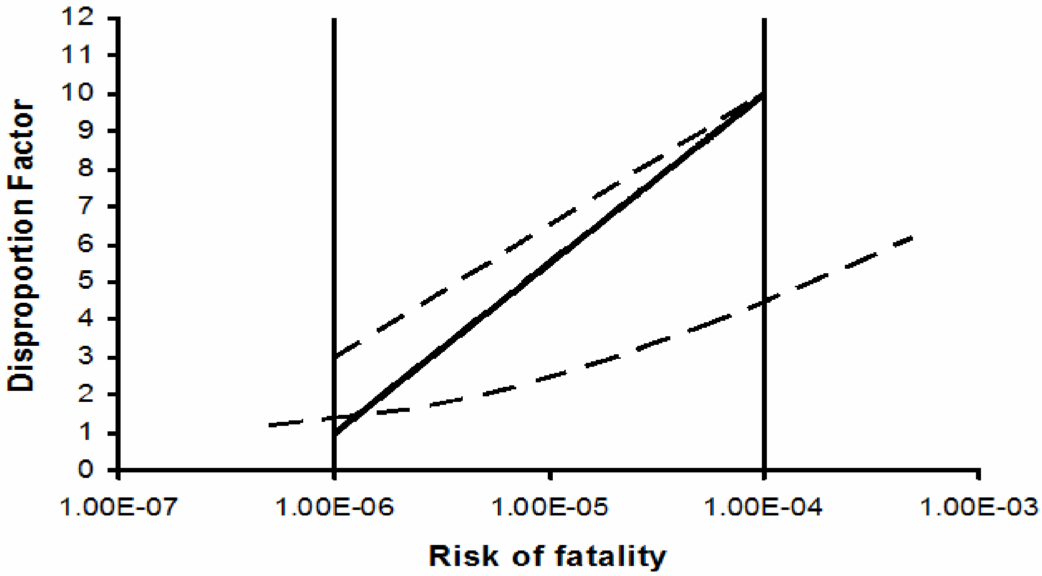

Figure 1: The proposed relationship between the ALARP disproportion factor and risk of individual fatality for the general public (solid line). The disproportion factor rises from 1 at the broadly acceptable risk level to 10 at the intolerable risk level in line with HSE guidance, but on a logarithmic scale of risk in line with suggestions by Bowles [11] (upper dotted line) and a multiplicative risk aversion factor from NRPB [13] (lower dotted line).

Turning to the case of workers, for whom there is considered to be some personal benefit to accepting a higher risk tolerance, Yasseri [15] suggests a disproportion factor rising linearly from 2 to 10 on a logarithmic scale of risk, although the broadly acceptable and intolerable limits in this paper are higher as they refer to existing risks in the offshore industry. The HSE submission to the Sizewell B enquiry [12] gives a value of 3 for workers but no risk level is specified. The NRPB multiplying factor for the greater risk range again provides a useful comparison [13]. Figure 2 illustrates these various references together with the relationship suggested here, which is a gross disproportion factor with value 1 for workers at the broadly acceptable level of 10^{-6} fatalities per year rising to 10 at the intolerability boundary of 10^{-3} fatalities per year again on a logarithmic scale of risk.

$$D_W = 3 \log_{10}(F) + 19 \tag{3}$$

Where: D_W is the ALARP gross disproportion factor for workers
F is the annual individual risk of fatality where $10^{-6} < F < 10^{-3}$

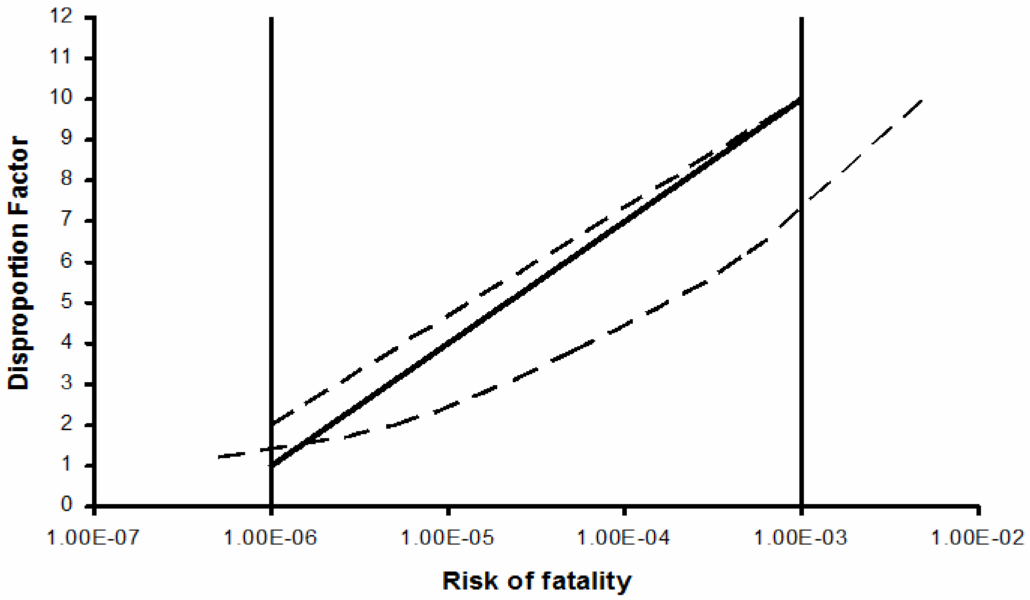

Figure 2: The proposed relationship between the ALARP disproportion factor and risk of individual fatality for workers (solid line). The disproportion factor rises from 1 at the broadly acceptable risk level to 10 at the intolerable risk level in line with HSE guidance, but on a logarithmic scale of risk in line with suggestions by Yasseri [15] (upper dotted line) and a multiplicative risk aversion factor from NRPB [13] (lower dotted line).

ALARP cost of a radiation protection intervention

A previous paper looked at whether the mechanisms of ALARP could be used to help with decision-making on radiation protection interventions by estimating the cost at which a given intervention becomes no longer 'reasonable' [16]. The approach is to use the collective dose saving to calculate the probability of avoiding a fatality. With the additional information about the cost of an attributable fatality C_F and the gross disproportion factor derived above (equation 1), this approach can be further refined. In the expressions below the gross disproportion factor has been redefined as a function of dose reduction again using the ICRP conversion factor from effective dose to fatal cancer risk of 0.05 per Sv [14] and the unit of effective dose has been set to mSv for convenience in practical radiation protection problems. The factor of 0.86 from equation 1 has been included. For the general public, the cost above which a radiation protection intervention is no longer ALARP becomes:

$$A_P \approx 4.3\text{x}10^{-5}\ V_F\ R\ N\ T\ [4.5\ \log_{10}(R) + 8.7] \qquad (4)$$

$$0.02\text{mSv/yr} < R < 2\text{mSv/yr}$$

and for workers:

$$A_W \approx 4.3\text{x}10^{-5}\ V_F\ R\ N\ T\ [3\ \log_{10}(R) + 6.1] \qquad (5)$$

$$0.02\text{mSv/yr} < R < 20\text{mSv/yr}$$

Where:
A_P is the cost above which a radiation protection intervention for the general public is no longer ALARP (£)
A_W is the cost above which a radiation protection intervention for workers is no longer ALARP (£)
V_F is the current monetary value of an attributable fatality (£)
R is the proposed annual dose reduction to the individual (mSv/yr)
N is the number of individuals to which the dose reduction will apply
T is the time over which the proposed intervention will apply (yr)

Examples of use in hospital radiation protection

Two of the following examples are the same as used in a previous publication [16] that used only directly citable fixed values for the gross disproportion factor and an 'upper end' value for the cost of a fatality. The current formulation of the ALARP limit and the inclusion of the years of life lost correction produce different results but the principle is the same.

Example 1: reduction of radiologist/cardiologist occupational doses

Investment in various relatively expensive products ranging from floor or ceiling supported heavy lead personal protective equipment to the use of remotely operated robots could be considered to reduce the occupational dose of radiologists/cardiologists to close to zero. The Health Protection Agency 2010 review of radiation exposure to the UK population gives an average figure of 0.11 mSv/yr occupational exposure for radiologists and 0.12 mSv/yr for cardiologists [17]. Taking the higher figure of 0.12 mSv/yr and supposing that 10 individual radiologists/cardiologists would be using the purchased equipment over a period of 5 years, then the upper limit to ALARP expenditure in the expression for workers above using the current value of V_F is £1503 over the 5 year period, or only £301 per year. This low figure reflects how well radiologist/cardiologist occupational doses are already controlled.

Example 2: design of a CT room

The designer of a computed tomography (CT) room has calculated that Code 4 lead plasterboard will be sufficient to protect a neighboring office occupied by three persons down to the required dose constraint of 0.3 mSv/yr. The designer is uncomfortable with this result and specifies Code 5 lead plasterboard instead to allow for possible future changes to equipment or workload. The change in lead thickness from 1.8mm to 2.24mm will result in lowering the yearly exposure to the three occupants from 0.3 mSv/yr to 0.1 mSv/yr [18] for the life-time of the CT scanner, which can be taken as 7 years [19]. From the expressions above using the current vale of V_F, the maximum ALARP cost of this intervention would be £1262 for three workers or £1751 for three members of the public e.g. volunteers. The wall extends 4m between the floor and ceiling slabs of the building and is 5m across. Using online quotes for lead plasterboard, the additional cost of the change from Code 4 lead to Code 5 is approximately £500, well within the ALARP cost for three people but marginal for one worker. The intervention is therefore ALARP in terms of cost, and the designer could use this in support of the decision to specify protection over and above that strictly required to meet the dose constraint.

Example 3: additional protective equipment and/or training for nuclear medicine staff

The Health Protection Agency 2010 review of radiation exposure to the UK population gives an average figure of 1 mSv/yr occupational exposure for nuclear medicine radiographers and technicians and 0.4 mSv/yr for nuclear medicine nurses [17]. Such specialist staff already work in an environment strictly controlled by the requirements of the Ionising Radiations Regulations 2017 [1], including Local Rules and the requirement of the employer to provide adequate radiation protection equipment and training. The relatively large average annual occupational exposure for this group does, however, suggest a possible cost-benefit value in attempting to reduce these levels.

A nuclear medicine department has 20 staff in these categories; 10 nuclear medicine radiographers and technicians, and 10 specialist nurses. If an annual radiation protection intervention could half the occupational exposure to this staff group then the maximum ALARP cost of the intervention would be £1950 for the radiographers and technicians plus £650 for the nurses (whose dose reduction would be smaller) or £2600 per year for the group using the current value for V_F. Such information might be of use in bidding for training funds or protective equipment.

Example 4: the ALARP value of reductions in CT patient doses

The UK Ionising Radiation (Medical Exposures) Regulations of 2017 [20] reflect the wording of the Euratom Directive from which they are derived [21] in requiring that ‘the operator must select equipment and methods to ensure that for each exposure the dose of ionising radiation to the individual undergoing the exposure is as low as reasonably achievable and consistent with the intended diagnostic of therapeutic purpose’. It is, however, difficult to directly link the cost-benefit definition of ALARP investigated here with individual patient doses, which are controlled by justification and optimization [21] and for which no fixed value of intolerable risk exists. The reduction in radiation exposure to the UK population resulting from recent reductions in doses for patients undergoing CT examinations can, however, be analyzed from the standpoint of an intervention benefiting public health.

The 2010 survey of radiation exposure to the UK population gives a figure for medical exposure from CT of 0.27 mSv per capita per year [17]. This is by far the highest component of man-made radiation exposure to the population. Taking the increase in number of CT scans in England from 4 million in 2010 [22] to 6 million in 2019 [23] to be representative of the proportional increase for the UK, and the increase in UK population from 62.8 million in 2010 to 66.8 million in 2019 [24], the figure of average medical exposure from CT would have been expected to rise from 0.27 mSv per capita per year in 2010 to 0.38 mSv per capita per year in 2019 if the scanners had stayed the same. The 2019 UK survey of CT scanner doses in fact shows a 20-30% decrease since the previous survey of 2011, due to the widespread introduction of scanners featuring iterative image reconstruction and automatic exposure control plus efforts in dose optimization [25]. Taking the average reduction in CT scanner patient dose over the period to be 25%, then the population average exposure from CT will have reduced from the predicted 0.38 mSv per capita per year in 2019 to 0.285 mSv per capita per year, a saving of 0.095 mSv per capita per year. If the programme of scanner replacement and optimization in the period 2010 to 2019 is recast as an intervention aimed at reducing the population radiation exposure from CT, then the value at which this intervention becomes no longer ALARP can be estimated. Taking the individual dose reduction to be 0.095 mSv/yr, the time period over which the intervention applies to be the 7 year average life-time of a CT scanner [19], the number of people to whom the saving applies to be the population of 66.8 million in 2019 [24] and using the current value for V_F, then the cost at which the intervention is no longer ALARP is, from equation 4, approximately £13.7bn over 7 years. If the number of CT scanners in the UK is taken as 607 [25], then the cost at which replacing a CT scanner becomes no longer ALARP is £22.6m, compared with the actual replacement cost of approximately £0.5-1m. The replacement of older CT equipment is driven by the improvements in clinical image quality, radiation dose efficiency, greater throughput etc. given by modern designs, but this analysis shows that it is also strongly indicated as an ALARP measure for public radiation protection.

Conclusions

UK guidance on cost-benefit analysis in support of ALARP has been used to formulate relationships for the estimation of the cost at which a radiation protection intervention is no longer ALARP. Although these relationships have no legal status, they are consistent with the guidance available and allow for a direct link between a reduction in radiation exposure and the maximum ALARP cost at which an intervention would still be considered to be reasonable. Examples of application to hospital-based radiation protection situations have shown that the ALARP cost limits for protecting radiation workers against the residual risks in the hospital environment are perhaps surprisingly low. Conversely, the ALARP limit to investment in population dose reduction by means of reducing patient doses can be very high.

REFERENCES

[1] The Ionising Radiations Regulations 2017 Available from: www.legislation.gov.uk/uksi/2017/1075/contents/made

[2] Health and Safety at Work Act 1974 The Stationary Office ISBN 978 010 543774 1 Available from: www.legislation.gov.uk/ukpga/1974/37/contents

[3] HSE 2001. Reducing Risks, Protecting People The Stationary Office ISBN 0 7176 2151 0 Available from: www.hse.gov.uk/risk/theory/r2p2.pdf

[4] HSE 2022. ALARP "at a glance" Available from: www.hse.gov.uk/managing/theory/alarpglance.htm

[5] Edwards v NCB 1949, Kings Bench, All England Law Reports 743 1

[6] HSE 2022 Principles of cost benefit analysis (CBA) in support of ALARP decisions. Available from: www.hse.gov.uk/managing/theory/alarpcba.htm

[7] HSE 2022 Cost benefit analysis (CBA) checklist. Available from: www.hse.gov.uk/managing/theory/alarpcheck.htm

[8] HSE 2016 Costs to Britain of work-related cancer. Research report RR1074 HSE Books. Available from: www.hse.gov.uk/research/rrpdf/rr1074.pdf

[9] HSE 1992 The tolerability of risk from nuclear power stations. HMSO, London. Available from: www.onr.org.uk/documents/tolerability.pdf

[10] HSE Guidance on ALARP Decisions in COMAH Available from: www.hse.gov.uk/foi/internalops/hid_circs/permissioning/spc_perm_37/

[11] Bowles D S 2003 ALARP evaluation: using cost effectiveness and disproportionality to justify risk reduction. ANCOLD conference on Dams.

[12] HSE 2022 Principles of cost benefit analysis (CBA) in support of ALARP decisions. Available from: www.hse.gov.uk/managing/theory/alarpcba.htm

[13] Webb G A M and Fleishman A B 1986 Valuations of health detriment in the optimization of radiological protection: a current NRPB view. Optimization of radiation protection, Vienna, 1986 pp 487-98 ISBN 92-0-020386-8

[14] ICRP 2007 The 2007 recommendations of the international commission on radiological protection. ICRP Publication 103. Annals of the ICRP 37; 2-4

[15] Yasseri S 2013. The ALARP argument. *FABIG newsletter* (61).

[16] Kotre C J 2022. When does reasonably practicable become rather pricey? *Brit J Radiol* 10.1259/bjr.20220612

[17] Oatway WB, Jones AL, Holmes S, Watson S and Cabianca T 2016. Ionising Radiation Exposure of the UK Population: 2010 Review. Public Health England report PHE-CRCE-026

[18] Sutton DG, Martin CJ, Williams JR and Peet DJ 2012. Radiation shielding for diagnostic radiology. British Institute of Radiology, London.

[19] RCR 2019. Implementing the NHS long-term plan call for written submissions: RCR response. Available from: www.rcr.ac/sites/default/files/final_implementing_the_ltp_submission.pdf

[20] The Ionising Radiation (Medical Exposure) Regulations 2017. Available from: www.legislation.gov.uk/uksi/2017/1322/contents/made

[21] European Council Directive 2013/59/Euratom 2013. Available from: www.legislation.gov.uk/eudr/2013/59/contents

[22] Public Health England 2014. Doses from computed tomography (CT) examinations in the UK – 2011 Review. Available from: https://assets.publishing.service.gov.uk/government/uploads/system//attachment_data/file/349188/PHE_CRCE_013.pdf

[23] NHS 2020. Diagnostic imaging dataset annual statistical release 2019/20. Available from: www.england.nhs.uk/statistics/wp-content/uploads/sites/2/2020/10/Annual-Statistical-Release-2019-20-PDF-1.4MB.pdf

[24] Office of National Statistics 2022. Overview of the UK population: 2020. Available from: www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/articles/overviewoftheukpopulation/2020#uk-population-data

[25] UK Health Security Agency 2022. UKHSA-RCE-1: doses from computed tomography (CT) exams in the UK 2019 review. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1084214/UKHSA-CT-report.pdf