Occupational Radiological Protection: How Safe Is Safe Enough?

Recommendations for α values, helpful for assessing the reasonableness of investments in occupational radiological protection

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With regard to the ALARA principle:
‘The letters ALA (as low as) have been enthusiastically embraced. One even senses the development of competition among institutions to be the lowest. […] The letters RA (reasonably achievable) are the poor ignored sisters.’ (1 p.397)
Mervyn D. Cohen, 2012

ABSTRACT

In the short term, a society's resources are limited, therefore making the prioritisation of needs unavoidable. For instance, the more financial resources a hospital allocates to radiological protection, the fewer remain available for other healthcare needs. With a focus on occupational radiological protection, the overall aim of this thesis was to answer the question: How safe is safe enough?

One way to approach this question is through a cost-benefit analysis, in which the direct costs of investments are balanced against the corresponding collective dose reductions. A fundamental challenge in employing cost-benefit analysis is determining a price for collective dose reductions, the so-called α value. By means of different health economics techniques, Papers I, II and III provide a range of α-value recommendations. For instance, acknowledging the uncertainties inherent in these methods, Paper II recommends α values between \$57 and \$171 per man·mSv for the Swedish general public and between \$62 and \$163 per man·mSv for Swedish workers (2023 USD). This implies that investments in occupational radiological protection below these intervals can be considered a good investment. For investments within these intervals, factors other than cost and collective dose are important to consider, whereas investments above these intervals can be considered too expensive.

Paper IV of this thesis promotes stakeholder involvement by asking staff members about discomfort associated with wearing lead aprons and thyroid collars for long periods of time, as well as their willingness to tolerate a small increase in future cancer risk to avoid wearing them. The results show that although discomfort was frequently reported, only a minority of staff would tolerate a minimal increase in future cancer risk to avoid wearing these protective tools, highlighting the complexity of making reasonable decisions about their use.

Keywords: Radiological protection, ALARA principle, cost-benefit analysis, value of a statistical life, α value, lead aprons

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POPULÄRVETENSKAPLIG SAMMANFATTNING

På kort sikt är ett samhälles resurser begränsade och måste prioriteras. Inom svensk sjukvård är budgeten ofta ansträngd; ju mer skattemedel som investeras i strålsäkerhet, desto mindre finns kvar till att finansiera övrig sjukvård. Med fokus på personalstrålskydd var det övergripande syftet i denna avhandling att försöka besvara frågan: Hur säkert är tillräckligt säkert?

En av huvudprinciperna inom strålsäkerhet är ALARA-principen ‘As Low As Reasonably Achievable’. Enligt denna princip framgår bland annat att exponering av joniserande strålning ska begränsas till att vara så låg som är rimligen möjligt med hänsyn till ekonomiska och samhälleliga faktorer. Ett sätt att uppnå denna princips syfte är att använda kostnadsnyttoanalyser. Inom strålsäkerhet används i sådana kostnadsnyttoanalyser oftast pengar som ett mått på både direkta investeringskostnader och på nyttan av dessa investeringar, uttryckt i form av kollektiv stråldosbesparing. Den största utmaningen ligger i att värdera vad en kollektiv stråldosbesparing är värd i pengar, vilket har fått benämningen α-värde.

I denna avhandling presenteras nya rekommendationer gällande α-värden som kan användas i kostnadsnyttoanalyser inom personalstrålskydd. Dessa rekommendationer baseras på ett hälsoekonomiskt mått, som benämns värdet av ett statistiskt liv och som beskriver människors betalningsvilja för att undvika en liten risk att dö. I delarbete I och II baseras de nya rekommendationerna gällande α-värden på värdet av ett statistiskt liv, som i sin tur är framtaget ur olika riskkontexter i samhället, exempelvis från trafiken. I delarbete III baseras α-värdet på värdet av ett statistiskt liv som i stället har hämtats från en kontext av strålningsinducerad cancer. I delarbete I ges även exempel på kostnadsnyttoanalyser inom personalstrålskydd i svensk sjukvård.

I delarbete IV lyfts personalens åsikter fram genom att fråga dem om trötthet i musklerna och smärta som de själva anser komma från att bära blyförkläde under långa tidsperioder. Dessutom tillfrågas personalen om de är villiga att tolerera en liten ökning av deras egen framtida cancerrisk i utbyte mot att slippa bära blyförkläden. Resultatet av delarbete IV pekar på komplexiteten i att fatta rimliga beslut gällande i vilka exponeringssituationer som personalen ska bära blyförkläden och i vilka situationer exponeringen bedöms tillräckligt liten för att det inte ska behövas. Av resultatet framgår att när en risk för cancer är uppskattad till större än noll, leder det lätt till oro. Hur liten risken egentligen är spelar en mindre roll.

LIST OF PAPERS

This thesis is based on the following papers, referred to in the text by their Roman numerals.

I. Engström A, Isaksson M, Javid R, Lundh C, Båth M. A case study of cost-benefit analysis in occupational radiological protection within the healthcare system. J Appl Clin Med Phys. 2021;22(10):295-304.

II. Engström A, Isaksson M, Javid R, Larsson PA, Lundh C, Wikström J, Båth M. How much resources are reasonable to spend on radiological protection?. J Radiol Prot. 2024;44(4):041516.

III. Engström A, Isaksson M, Javid R, Larsson PA, Lundh C, Båth M. An estimation of the monetary value of the person-Sievert useful for occupational radiological protection within the healthcare system of Sweden. Health Phys. 2024;127(5):569-580.

IV. Engström A, Isaksson M, Larsson PA, Lundh C, Båth M. Lead aprons and thyroid collars: to be, or not to be?. J Radiol Prot. 2023;43(3):031516.

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ABBREVIATIONS

ALARA	As low as reasonably achievable
ALARP	As low as reasonably practicable
CI	Confidence interval
CBA	Cost-benefit analysis
DAT	Decision-aiding technique
DR	Discount rate
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IQR	Interquartile range
ISOE ETC	Information System on Occupational Exposure, European Technical Centre
LNT	Linear no-threshold
NYEC	Number of years between exposure to ionising radiation and cancer diagnosis
OECD	Organisation for Economic Co-operation and Development
QALY	Quality-adjusted life year
VSL	Value of a statistical life
WTA	Willingness to accept
WTP	Willingness to pay

DEFINITIONS IN SHORT

α value	‘A dimensional constant expressing the cost assigned to the unit collective dose for radiation protection purposes.’ (3 p.18)
ALARA principle	‘The likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors.’ (4 p.14)
Cost-benefit analysis within radiological protection	‘An equation that defines the best or optimum solution as the option that minimises the overall cost, i.e. the total of the financial costs and the costs of health detriment.’ (5 p.22)
Value of a statistical life	‘This is not the value of a life, it is the value of a small change in the risk or probability of losing a statistical life.’ (6 p.62)


PROS
CONS

1 PROLOGUE

Suddenly, I was stopped in the corridor by a stressed nurse: ‘My back really hurts! Because of the lead apron, as we had to operate for over an hour and a half.’ It was not the first time I had heard this, but the only response I could muster was: ‘I feel for you’. The nurse continued to chatter, but all I could think of was that if she completely stopped wearing a lead apron in her work, she would probably not be exposed to more than 1 mSv per year (the same level as natural background radiation). Should I tell her? My gut feeling told me not to.

A couple of days later (at home on the sofa), my wife described a lecture she had attended about a new drug and how a cost-benefit analysis (CBA) would help decide whether or not it would be implemented in the Swedish healthcare system. In some way, this CBA was supposed to help evaluate if the benefits for the patients could be counterbalanced against the costs of the new drug. I thought to myself, maybe I can do something similar within radiological protection. That would be new and interesting!

Reading up on the subject, I was surprised to find that the International Commission on Radiological Protection (ICRP) had introduced the concept of CBA in radiological protection as early as 1973 (7). How come that I had studied to become a medical physicist and worked for about seven years, yet had never heard of it? To make sure, I checked with my closest colleagues: they had not heard about it either. Why was the CBA technique not applied more frequently in radiological protection within the Swedish healthcare system? Is it possible to perform a CBA on lead aprons, and if so, what would the result be? A spark had been ignited inside me.

2 INTRODUCTION

In 1928, the International X-ray and Radium Protection Committee was established as a response to concerns about the health effects observed after exposure to ionising radiation (8). Later, in 1950, the organisation changed its name to the present one, the International Commission on Radiological Protection. They present themselves as (8): ‘An independent, international organisation that advances for the public benefit the science of radiological protection, in particular by providing recommendations and guidance on all aspects of protection against ionising radiation’. This non-profit organisation comprises around 350 globally recognised experts and is organised around a main commission, a scientific secretariat, four standing committees and several task groups. Over the years, the ICRP has issued more than 150 publications on many different aspects of radiological protection. Several Swedish experts have played prominent roles in the work of the ICRP. Notably, Rolf Sievert served as chairman of the main commission both in 1928 and during the period from 1956 to 1966. Bo Lindell served as chairman from 1977 to 1985, and Lars-Erik Holm held the same position from 2005 to 2009 (8). In addition, Jack Valentin served as Editor-in-Chief of the ICRP’s scientific secretariat from 1997 to 2009, and was the lead editor of the ICRP’s 2007 general system of radiological protection, published as ICRP Publication 103 (4).

Within the ethical framework, the ICRP relies on four core values: beneficence/non-maleficence, prudence, justice and dignity (9). Beneficence/non-maleficence is described as doing good and avoiding doing harm. Prudence concerns ‘making informed and carefully considered choices without full knowledge of the scope and consequences of an action’ (9 p.11). As an example of prudence, the ICRP refers to the uncertainty in risks of exposure. Justice is explained as fairness in the distribution of both risks and benefits associated with exposure. A prerequisite of dignity is that every person deserves unconditional respect, which can be exemplified as stakeholder involvement (9). Together with these four core ethical values, the ICRP also states the following three key principles for radiological protection (4): justification, optimisation of protection and application of dose limits. The principle of justification means that any alteration of radiation exposure should only be considered if it does more good than harm, which is directly linked to the core ethical value of beneficence/non-maleficence (9). The principle of optimisation of protection (which this thesis focuses on) can be linked to the core ethical values of prudence, justice and dignity (9). The principle of optimisation of protection is also known as the ALARA principle, an acronym from the part of the principle that states: As Low As Reasonably Achievable. Finally, the principle of application of dose limits is mainly linked to the core ethical value of justice by limiting the risk for those most exposed (9).

2.1 THE ALARA PRINCIPLE

The history of the ALARA principle is described in detail in ICRP Publication 101b (10). Its origin can be traced back to the 1954 ICRP Publication (10,11 p.57) and the formulation: ‘that every effort be made to reduce exposures to all types of ionising radiation to the lowest possible level’. A few years later (in 1959) the ICRP reworded this statement to focus more on how far it is practicable to reduce exposures, formulating it as follows (10,12 p.11): ‘all doses be kept as low as practicable and that any unnecessary exposure be avoided’. A considerable step in the development of the ALARA principle was taken in ICRP publication 9 (published in 1966) (10,13 p.10), where the principle was defined in the following way: ‘As any exposure may involve some degree of risk, the Commission recommends that any unnecessary exposure be avoided, and that all doses be kept as low as is readily achievable, economic and social considerations being taken into account’. This statement has many similarities with the present formulation of the ALARA principle, focusing on both ‘as low as is readily achievable’ and ‘economic and social considerations being taken into account’. Minor revisions were made in ICRP Publication 22 from 1973 (7,10), where the word ‘readily’ was replaced by ‘reasonably’, and in ICRP Publication 26 from 1977, where the word ‘considerations’ was replaced by ‘factors’ (10,14). Later, in 1990, a more extensive supplement to the ALARA principle was introduced in ICRP Publication 60 (10,15 p.18), where the ICRP stated that optimisation involves: ‘the magnitude of individual doses, the number of people exposed and the likelihood of incurring exposures’. As reported by Wieder et al. (16), the latest amendment in ICRP Publication 103 from 2007 (4) replaces the word ‘social’ by ‘societal’ in the phrase ‘taking into account societal factors’. In its most recent form (from 2007), the ALARA principle now reads (4 p.14):

> ‘The likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors.’

The ALARA principle is useful in all three types of exposure situation defined by the ICRP: planned, emergency and existing (4). Regarding planned exposure situations (where sources are deliberately introduced and utilized), the ALARA principle is only applicable below the ICRP dose limits. The effective dose limits are set at 1 mSv per year for the general public and 20 mSv per year for workers; for workers, the effective dose is averaged over five years, with a maximum of 50 mSv allowed in any single year (4). Moreover, in planned exposure situations, the ICRP has also introduced the concept of ‘dose constraints’ for ALARA principle applications. A dose constraint is set by the licensee (below the dose limit) and described as ‘a level of dose above which it is unlikely that protection is optimised for a given source of exposure, and for which, therefore, action must almost always be taken’ (4 p.94). A similar concept is ‘reference levels’, which was introduced by the ICRP for emergency and existing exposure situations. Compared to the dose constraint, a reference level can be regarded as somewhat less stringent, since the ICRP has stated: ‘Efforts should, however, be aimed at reducing any exposures that are above the reference level to a level that is below, if possible.’ (4 p.96).

The International Atomic Energy Agency (IAEA), which comprises 180 member states (17), has incorporated the ALARA principle into its International Basic Safety Standards (18). One of the modifications of the ALARA principle made by the IAEA was to specify that environmental factors should also be taken into account. Furthermore, they clarified that the meaning of the ALARA principle is (18 p.7): ‘that the level of protection would be the best possible under the prevailing circumstances’. The European Union has published a directive regarding protection against exposure to ionising radiation called the Euratom Basic Safety Standards (19). In their version of the ALARA principle, apart from taking economic and societal factors into account, they also stressed the importance of considering ‘the current state of technical knowledge’ (19 p.12). European Union member states are obligated to achieve the goals of the Union’s directives (20), and Sweden has implemented the Union’s version of the ALARA principle in the Swedish Radiation Protection Act (21).

Just as the phrasing of the ALARA principle has evolved over time, the recommendations of how to implement it in practice have done likewise (10). These implementation recommendations started when the ICRP introduced CBA as a quantitative decision-aiding technique (DAT) in ICRP Publication 22 from 1973 (7,10). As a quantitative tool, CBA was presented for determining a level of radiological protection that could meet the criteria of ‘as low as readily achievable, economic and social considerations being taken into account’ (7 p.4). When this level of protection was achieved, it would represent a scenario where the ‘economic and social gains of further reducing the dose are equal to the economic and social costs of achieving that reduction’ (7 p.4). In 1983, the ICRP followed up with a more detailed description of CBA in publication 37 (3,10) and in 1989 the ICRP also reported on other quantitative DATs such as: cost-effectiveness analysis, multi-attribute utility analysis and multi-criteria outranking analysis (22). However, over time it became evident that in some radiological protection scenarios it is difficult to capture all relevant factors in a quantitative DAT. The ICRP therefore stated in publication 77 (from 1997) (23 p.14) that the ALARA principle is: ‘more subtle and judgmental than is implied by differential cost-benefit analysis’. This perspective was further developed in ICRP publications 81 and 82 (10,24,25), which discuss the limitations of quantitative DATs and advocate for the inclusion of stakeholder involvement, rather than relying solely on radiation protection experts. In the ICRP’s most recent publication on this topic, publication 101b from 2006 (10), it is stated that quantitative DATs are still valid but should only be seen as one input to the decision-making process. It is recommended to view the ALARA principle in a broader perspective, where qualitative approaches such as individual equity, safety cultural and stakeholder involvement are important (10). The ICRP task group 114 is now working to further develop practical advice concerning reasonableness and tolerability within radiological protection. The task group sees optimisation as a ‘process of active evaluation, which may be numeric, but is more likely procedural’ (16 p.2). In this context, it can also be mentioned that the IAEA’s interpretation of the ALARA principle is that (18 p.7): ‘Optimization is a prospective and iterative process that requires both qualitative and quantitative judgements to be made’.

The acronym ALARP (As Low As Reasonably Practicable) is closely related to ALARA (26). ALARP originates from the laws of the United Kingdom in the Health and Safety at Work etc. Act 1974 (27), where the wording of ‘so far as is reasonably practicable’ is frequently applied (26,27 p.4–10). Subtle differences between these acronyms might occur. Bryant et al. (26) report that the ALARP acronym is applied to all kinds of risks in contrast to the ALARA acronym, which exclusively refers to radiological risks. Shrader-Frechette and Persson (28) state that the word ‘achievable’ in the ALARA acronym refers to science, unlike the word ‘practicable’ in the ALARP acronym that leans more towards economic considerations. However, in practice ALARA and ALARP are seen as interchangeable terms (26). Within dental medicine, variations of the ALARA principle have also been introduced, including ALADA (As Low As Diagnostically Acceptable) and ALADIP (As Low As Diagnostically Acceptable being Indication-oriented and Patient-specific). These acronyms highlights the importance of practical guidelines and personalised optimisation in diagnostic imaging (29–31).

2.2 QUANTITATIVE DECISION AIDING TECHNIQUES

The ICRP states that optimisation should not be seen as minimisation and that 'the best option is not necessarily the one with the lowest dose' (4 p.92, 10 p.73). This is the context in which DATs belongs. In the literature, several different quantitative DATs are reported to be useful within radiological protection (3,5,7,10,14,22,32–34). This section presents a description of four main DATs: cost-effectiveness analysis, CBA, multi-attribute utility analysis and multi-criteria outranking analysis. What can be considered as sub-DATs of each main DAT are also briefly reported. Which DAT to apply often depends on the exposure scenario and the ability to quantify the relevant factors involved (5,22).

2.2.1 COST-EFFECTIVENESS ANALYSIS

In cost-effectiveness analysis the costs of radiological protection are compared (typically on a graph) to the exposure for each protection option (5,10,22,32). In Figure 1, a fictitious example of a cost-effectiveness analysis is presented, and similar examples have been published in the literature (5,10,22,32). The costs of eight different radiological protection options (A-H) are plotted against the exposure of each option. Options that are aligned on the cost-effectiveness curve (options A-D) can be deemed cost-effective in contrast to adjacent options (E-H). Option D is seen as the 'zero option', representing no further investments in radiological protection. In this context, cost-effectiveness analysis is not a DAT that can be applied to find the optimum solution, but rather a technique for ruling out adjacent options that are projected to be non-cost-effective (10,22).

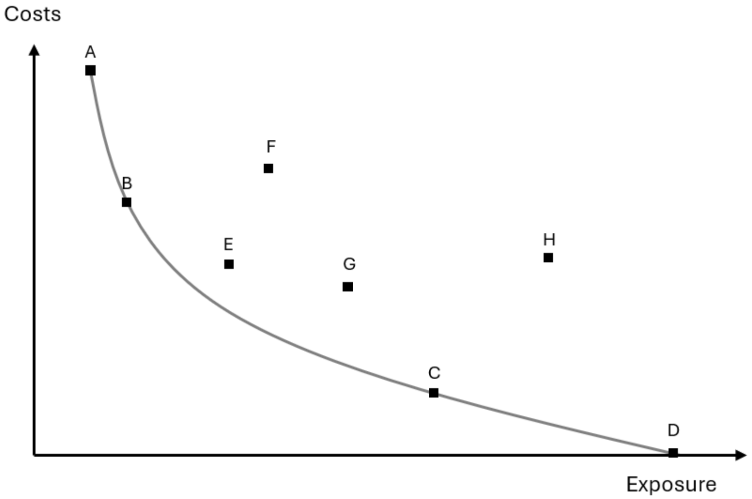

Figure 1. Four radiological protection options (A-D) are aligned on the cost-effectiveness curve, while the other four options (E-H) are considered non-cost-effective.

2.2.2 COST-BENEFIT ANALYSIS

The first DAT to be introduced for radiological protection by the ICRP (7) was CBA, which can be seen as the foundation of other DATs. In general terms, the cost-benefit balance in an exposure scenario can be described by Equation 1, where B is the overall net benefit of a scenario, V the gross benefit, P the general costs, X the costs of radiological protection, and Y the cost of health detriment at that level of radiological protection (3,7,32):

$$B = V - (P + X + Y) \qquad \text{Equation 1}$$

A CBA applied in radiological protection can be seen as an equation that defines (5 p.22): ‘the best or optimum solution as the option that minimises the overall cost, i.e. the total of the financial costs and the costs of health detriment’. Referring to Equation 1, this corresponds to the minimum total costs of the sum of $X + Y$. In this way, the total cost CBA method can be a helpful tool for decision-makers when choosing between several options, where the outcome can be interpreted as the option that will meet the criteria of the ALARA principle (7).

In the simplest form of the total cost CBA method, the sum of the costs of the radiological protection factor and the costs of the health detriment factor ($X + Y$) are compared between different options. To achieve this comparison, the health detriment factor is usually expressed in monetary terms. Using

Equation 2 (3,5,32,35), the health detriment factor Y can be expressed in monetary terms by applying an α value that is defined as a ‘dimensional constant expressing the cost assigned to the unit collective dose for radiation protection purposes’ (3 p.18), where S represents the collective dose:

$$Y = \alpha S \qquad \text{Equation 2}$$

As a fictitious example of the total cost CBA method, staff working in an operating theatre (used for percutaneous coronary intervention) are exposed to a collective dose of 10 man·mSv per year. Option A is to maintain the present level of radiological protection in the operating theatre, referred to as the zero option. Option B is to purchase an overhead X-ray shield at a cost of $5,000. This overhead shield is assumed to be used for 10 years before disposal and to decrease staff member’s collective dose to 2 man·mSv per year. Option C is to complement the overhead shield with radiation protective drapes for femoral and radial access. However, these drapes must be used with sterile disposable covers that should be replaced for each patient. The cost of option C for the next 10 years is estimated to be $20,000 (overhead shield, radiation protective drapes and sterile disposable covers). In option C staff members are assumed to be exposed to 1 man·mSv per year. In this fictitious example, the α value was set at $500 per man·mSv, and the CBA result over the 10-year period is presented in Table 1. Given the assumptions of this total cost CBA, Option B emerges as the optimal solution, as it minimises the total cost ($X + Y$).

Table 1. Comparison of three different radiological protection options (A-C) over a 10-year period in an operating theatre.

Option	Costs of radiological protection (X) [$]	Costs of health detriment (Y) [$]	Total costs of option ($X + Y$) [$]
A	-	50,000	50,000
B	5,000	10,000	15,000
C	20,000	5,000	25,000

Another way to analyse this fictitious example is to use the differential CBA method (5). With this technique, adjacent options are compared with each other. Moving from option A to option B (in Table 1) will increase the costs of radiological protection by $5,000, while at the same time decreasing the collective dose by 80 man·mSv for the next 10 years. A cost-benefit ratio of these two factors can be calculated as $62.5 per saved man·mSv. With an α value set at $500 per man·mSv, the move from option A to option B has a lower cost-benefit ratio and can therefore be considered a good investment.

When moving from option B to option C, the costs of radiological protection are increased by \$15,000 (due to the cost of radiation protective drapes and sterile disposal covers) and the collective dose reduction (for the next 10 years) is assumed to be 10 man·mSv. The cost-benefit ratio is calculated as \$1,500 per saved man·mSv. With the α value set at \$500 per man·mSv, the move from option B to option C is considered too expensive. In the differential CBA method, the optimal solution is the one with the greatest cost-benefit ratio among those options that score under the determined α value. In mathematical terms, the total cost CBA method and the differential CBA method are equivalent and will produce the same answer in terms of what is considered the optimum solution (5). Several reports (5,7,10,22,33,36) have presented a graphical depiction of the optimum solution when only two factors are considered: the costs of radiological protection X and the costs of health detriment Y. This relationship is graphically illustrated in Figure 2.

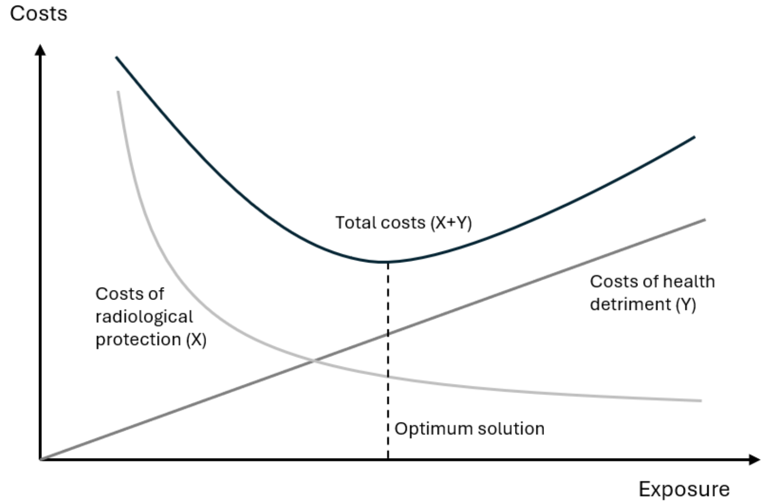

Figure 2. A graphical illustration of the costs of radiological protection X, the costs of health detriment Y and the total cost of options ($X + Y$). The optimum solution is also indicated.

An extended CBA can be applied in order to include relevant factors other than the costs of radiological protection and the costs of health detriment (22). For example, a factor such as individual doses can be considered, which can be described by means of a β value. The costs assigned to an individual dose level (the β value) are simply added to the α value to represent the total costs of health detriment (5,22). In this way, two radiological protection options with the same protection costs and collective doses can still be distinguished if they differ in individual dose levels. Options with relatively high annual individual doses are discarded in favour of those with the same collective dose but a more homogeneous distribution of exposure. Another factor that can be incorporated in an extended CBA is presumed differences in the costs of health detriment between the general public and workers. Differences in costs assigned to exposure in the distant future compared to current exposure can also be taken into account (5,22). In an extended CBA all relevant factors are expressed in the same monetary unit. If the relevant factors are qualitative by nature, in ways that are cumbersome to express in monetary terms, then a multi-attribute utility analysis might be the preferred DAT to use (5,22,33,35).

2.2.3 MULTI-ATTRIBUTE UTILITY ANALYSIS

In multi-attribute utility analysis, qualitative factors (on ordinal scales) are converted into quantitative ones (on interval scales) (5,10,22,32). As a fictitious example, the discomfort associated with wearing a lead apron for a long period of time (a qualitative factor) can be ranked on an ordinal scale depending on the apron's weight. An ordinal scale from 'difficulty working', 'slight problem working' to 'no problem working' can be used and thereafter converted (with different option scores) into an interval scale: 0 for 'difficulty working', 0.5 for 'slight problem working' and 1 for 'no problem working'. This approach is problematic as it exaggerates the ordinal scale information by assuming a fixed distance between the qualitative terms (37–39). However, in multi-attribute utility analysis, these option scores do not need to be linearly distributed and are seen as a part of the subjective judgmental nature of the DAT (5,10,22). In this framework, the qualitative discomfort factor associated with wearing a lead apron can be compared with other quantitative factors, such as the costs of different models. In the fictitious example, the most expensive lead apron model was assigned a score of 0 (representing the least favourable option from an economic perspective), while the absence of a lead apron was assigned a score of 1 (representing the most favourable option from an economic perspective). Intermediate alternatives were given proportionally interpolated scores. Another relevant factor is staff member's exposure to ionising radiation when wearing different lead apron models, which is associated with the lead thicknesses of the apron and therefore also with the weight and discomfort of wearing it. Following the same scoring logic, the option with the highest exposure was assigned a score of 0 (least favourable), and the option with the lowest exposure was assigned a score of 1 (most favourable), with intermediate values again determined by interpolation. In this fictitious example the three options were:

- Option A, not wearing a lead apron, which was considered to cause ‘no problem working’ (score 1), zero costs (score 1) but an effective dose of 11 mSv per year (score 0).
- Option B, wearing a lead apron with a lead thickness of 0.5 mm and a weight of 5 kg. It was considered to cause ‘a slight problem working’ (score 0.5), costs $500 (score 0.5) and an effective dose of 2 mSv per year (score 0.9).
- Option C, wearing a lead apron with a lead thickness of 1 mm and a weight of 10 kg. It was considered to cause ‘difficulty working’ (score 0), costs $1,000 (score 0) and an effective dose of 1 mSv per year (score 1).

The next step in the multi-attribute utility analysis is to assign weighting scores to different factors. For the sake of simplicity in this example, it was decided to assign a double weight to exposure to ionising radiation in contrast to the other two factors. The outcome of the analysis is presented in Table 2. As can be seen, option B (a lead apron with a lead thickness of 0.5 mm) received the highest total score and is therefore considered the optimum solution. In multi-attribute utility analysis, the subjective scores assigned to different factors and the weighting scores between factors are often fundamental to the outcome of the analysis. In this example, if the three different factors had received the same weighting score, option A (not wearing a lead apron) would have been considered the optimum solution. To mitigate this problem, a sensitivity analysis is often conducted, where different factor scores and weighting scores between factors are tested, to determine the robustness of the multi-attribute utility analysis outcome (5).

Table 2. A multi-attribute utility analysis of a fictitious example of lead aprons.

Option	Discomforts [0-1] [a]	Costs [0-1] [a]	Exposure to ionising radiation [0-1] [b]	Total score
A	1	1	0	2.0
B	0.5	0.5	0.9	2.8
C	0	0	1	2.0

[a] A weighting score of 1 was applied in calculating the total score.

[b] A weighting score of 2 was applied in calculating the total score.

Kepner-Tregoe decision analysis can be seen as a form of multi-attribute utility analysis (32). A team of experts is asked to judge both the scores of the different factor options and the weighting scores between factors. It has been suggested that the more intangible and qualitative the data, the more experts should be included in the team assessing them (32).

In 2023, Wattier et al. (34) suggested life cycle assessments as a supplement to multi-attribute utility analysis. A life cycle assessment focuses on both the environmental and the human health impacts of a product or a service and often applies a time horizon from cradle to grave. Wattier et al. (34) provide an example about the thickness of a concrete wall used for radiological protection. Apart from the more common factors of exposure to ionising radiation and the financial costs of building the wall, a life cycle assessment can include impacts such as mineral resource use, water consumption, terrestrial ecotoxicity and global warming. In this way, a life cycle assessment can be applied to incorporate all the impacts of producing the actual radiological protection option (34).

2.2.4 MULTI-CRITERIA OUTRANKING ANALYSIS

A multi-criteria outranking analysis can be applied in scenarios where it is considered impossible to compare all relevant factors with each other by transforming them into one single figure of merit (22,32). As the name suggests, a multi-criteria outranking analysis is used to assess if one option outranks another. Referring to the example about lead aprons in Section 2.2.3, it might be considered that a specific level of exposure to ionising radiation cannot be fully compensated for by the other two relevant factors, that is, the costs of the lead apron and the discomfort of wearing it. In that scenario, an exclusion criterion can be applied to a specific level of exposure (such as the ICRP dose limits (4)), meaning that those options will be outranked by the other options (22,32).

The analytical hierarchy process analysis is a form of multi-criteria outranking analysis and can be seen as a parallel method to the Kepner-Tregoe decision analysis. In an analytical hierarchy process analysis, a team of experts decide on the quantitative scores of pairwise comparisons between factors as well as pairwise comparisons between the extent to which the different options fulfil these factors to determine the optimum solution (32). A detailed description of the mathematical methods involved in an analytical hierarchy process analysis has been provided by the U.S. Department of Energy (32).

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2.3 SENSITIVITY ANALYSIS

The application of a DAT usually involves several uncertainties, both in measured factors such as the collective dose, and in judgment-based factors, such as the α value (5,10,22). Furthermore, uncertainties arise due to the possibility that some relevant factors might have been left out as well as options of radiological protection that have been foreseen. A sensitivity analysis is merely a way of addressing the uncertainties involved and asking ‘What if?’ (5). A simple way to conduct a sensitivity analysis is to alter the score of one factor at a time and recalculate the DAT to see if the outcome is changed. Analysing the factors individually also provides insight into which ones warrant more thorough consideration (5,22). It is important to be realistic when assigning factor scores, especially in the case of judgment-based factors. Being over-pessimistic when scoring factors (applying a worst-case scenario) can lead to situations where other societal opportunity costs are missed (5,32). It is also unlikely that all factors included in a DAT will turn into an extreme score at the same time. One solution can be to implement a sensitivity analysis by means of Monte Carlo simulations (a technique employed in Paper II). If the DAT outcome remains after recalculation in a sensitivity analysis, the decision-maker can be certain that the outcome is robust. On the other hand, if the sensitivity analysis shows that the DAT outcome is sensitive to realistic alterations, then it cannot be fully trusted. However, the decision-maker will then know that none of the protection options can be proven to be an optimum solution (5). In this scenario, the decision-maker needs to rely to a greater extent on personal judgment (5,10).

2.4 THE ALPHA VALUE

Two of the most fundamental factors in radiological protection are the costs of protection and the exposure to ionising radiation. These two factors are often interrelated, as greater investment in protection typically leads to reduced exposure. When working with these factors in CBAs, the most complicated aspect is often determining which α value to use (10). It is the responsibility of each operating management to adhere to the ALARA principle (10) and to determine the α value most relevant to the given scenario (40). This situation has resulted in the application of a broad range of α values, even within countries and geographical areas with similar economic status (40,41). The determination of an α value is linked to a concept within health economics called ‘the value of a statistical life’ (VSL) (42), described in more detail in Section 2.5. Since the introduction of the α value and its link to VSL in 1973, concerns (some of them ethical) have been raised regarding its determination and application, many of which remain unresolved (10). Nevertheless, in recent decades significant steps have been made within health economics concerning the estimation of VSL (43).

Based on the author's experience as a medical physicist, the application of CBAs in radiological protection within the Swedish healthcare system is very limited. It is also difficult to find α-value recommendations that can be easily applied, especially ones based on a solid evidentiary foundation. Furthermore, to the best of the author's knowledge, only a few examples of CBAs in radiological protection in the healthcare system can be found in the literature (44–47). It is from this circumstance that two of the four specific aims of this thesis emerged: (i) to develop new α-value recommendations applicable to occupational radiological protection (as presented in Papers I, II and III), and (ii) 'to describe cases of CBAs in occupational radiological protection within the Swedish healthcare system' (as presented in Paper I p.297). The specific aims of this thesis are also presented in Section 3.

2.5 THE VALUE OF A STATISTICAL LIFE

It is difficult to find a generally agreed definition of VSL. In economic terminology, VSL has been described by Cameron (42 p.161) as 'a marginal rate of substitution between mortality risk and money (i.e., other goods and services)'. From a practical perspective, the Department of the Prime Minister and Cabinet of the Australian Government (48 p.1) defines VSL as 'an estimate of the value society places on reducing the risk of dying'. HM Treasury, the economic and finance ministry of the United Kingdom (6 p.62), states the following regarding VSL: 'This is not the value of a life, it is the value of a small change in the risk or probability of losing a statistical life'. This statement addresses a frequent misconception about the VSL concept, as it is often wrongly interpreted as just 'the value of a life' by the general public (42). Therefore, in 2010 Cameron (42 p.163) suggested replacing the phrase 'the value of a statistical life' by 'the willingness to swap', in order to stress that the concept focuses on the willingness to swap 'goods and services for a microrisk reduction in the chance of sudden death'. However, this suggested phrase does not seem to have become widespread.

Two prerequisites for applying the concept of VSL are: (i) the estimated risk must be close to zero for every individual and (ii) the individuals involved should not be able to be identifiable (49). For instance, in contexts such as road safety and radiological protection, both conditions are typically met: the individual risks are close to zero, and within a relatively large population it is not possible to know in advance which individuals may be affected. By contrast, in a scenario where only a few people are trapped in a cave, neither of the two conditions are fulfilled, thus the VSL concept is not applicable (49).

In the past, the human capital approach was the most common method of estimating a VSL (43,50). This purely economic approach is based on a society's loss of production due to losing a statistical life. It can be measured by the expected lifetime earnings for those exposed to the risk, or by the gross domestic product per year and capita, together with the mean number of years lost for those affected by the risk (50). Either way, the human capital approach implies that unproductive individuals (because of retirement, unemployment, parental leave or sick leave) are not as valuable as members of the workforce. Such an implication is often considered unethical (51). Moreover, the human capital approach fails to account for individuals' preferences regarding life and health, as well as their attitudes toward risk aversion (43,50). However, several examples of α-value recommendations from 1985 to 2019 based on the human capital approach can be found in the literature (52–61).

Another method to estimate VSL is the revealed preference approach which relies on observational data from people's behaviour in real life situations (43,50). This approach can typically be divided into consumer market studies and wage-risk studies (50). An example from consumer market studies involves dividing the extra amount a buyer pays for a safer car by the estimated reduction in fatality risk provided by its safety features (62). One criticism of consumer market studies is that some safety features are inexpensive (for example medical diagnostic tests or smoke detectors) compared to their probability of saving a life. Wage-risk studies are one of the most common forms of VSL estimates (43,50). This approach is based on the assumption that a job with a high risk of mortality or morbidity will offer a higher wage compared to a less risky job, when all other wage-related factors are controlled for (50,63). An advantage of wage-risk studies is the ease of access to high quality data (50). However, there are also concerns about wage-risk studies. For example, workers may not have knowledge of the risk involved in the job they are applying for and there are usually several circumstances in life that prevent workers from moving freely between jobs (50). To the best of the author's knowledge, only one α-value recommendation based on the revealed preference approach has been published. This recommendation applied to China and was published in 2019 by Linsheng et al. (61).

Today, the stated preference approach is the most common research method for estimating VSL (33,64,65) and it is preferred over the human capital approach (50,66). The stated preference approach is based on surveys, where the respondents answer questions about, for example, their willingness to pay (WTP) to avoid a small risk of death within a specific context (43,50,65). To illustrate, in a society of 10,000 individuals, an average of two die every year in traffic accidents. What is that society's WTP per year to decrease that risk to an average of only one individual per year? When surveyed, each of the 10,000 individuals might be willing to pay a mean of $100 per year. In such a case, that society's VSL can be calculated as $1 million (100 × 10,000) in that specific context (49). The stated preference approach has several shortcomings. One of them is hypothetical bias, whereby respondents might overestimate their WTP in a survey compared to real-life situations (67–69). Another is respondents' scale-insensitivity, which refers to the observation that respondents' stated WTP to avoid a risk is not proportional to the magnitude of the presented risk reduction (69–72). Furthermore, it has been shown that respondents' WTP to avoid a risk is usually lower than their willingness to be compensated for tolerating the same risk, that is, their willingness to accept (WTA) the risk (73).

Since it typically does not exist studies of the stated preference approach of VSL for each specific risk context and society, VSL estimates from other risk contexts or societies can be used with appropriate adjustments. This approach is called a 'benefit transfer' (64). For example, a meta-analysis of VSL estimates from a wide range of risk contexts can be 'transferred' and applied in CBAs within a specific risk context. The strength of applying a benefit transfer of a general VSL estimate is that limited financial resources can be equally distributed between risk contexts in a society. There are several examples of α-value recommendations based on a benefit transfer of the stated preference approach (44–46,51,74,75). Papers I and II of this thesis add to that list. However, several studies have shown that VSL estimations based on the stated preference approach are dependent on the risk context, despite the fact that the magnitude of the presented risk reduction is identical (49,51,65,76–79). It should be noted that some studies have also yielded the opposite result, namely that VSL is not context-dependent (80–83). Moreover, assuming that VSL is context-dependent, it can be appropriate to recommend α values based on the stated preference approach with a specific VSL estimate in radiological protection. To the best of the author's knowledge, there are only a few examples of such recommendations (54,84–86), all of which were published between 1999 and 2003 and derived from the nuclear industry. Paper III adds to these examples, the main difference being its context within the healthcare system. The distinction between using a general VSL through benefit transfer and applying a context-specific VSL estimate will be further discussed in Section 5.4 and Section 5.5.

2.6 HOW TO CONVERT SOCIETAL COSTS INTO AN ALPHA VALUE

The societal costs of losing a statistical life encompass several different aspects, such as the VSL, productivity losses and healthcare costs. The VSL is the most common societal cost for determining an α value. However, the conversion of a VSL into an α value is problematic. The conversion method most frequently applied is to multiply the VSL by the risk of the consequence (radiation-induced cancer), expressed as the ICRP's detriment-adjusted nominal risk coefficient (4). Several examples of α-value recommendations based on this conversion method can be found in the literature (44,51,54,74,85,86). However, this method can be deemed overly simplistic, as it presumes an instant consequence of the risk. In reality, several decades generally pass between exposure to ionising radiation and the risk of radiation-induced cancer (90).

One way to try to get around this problem has been to apply an annual VSL together with an estimation of the average years of life lost from radiation-induced cancer death. In ICRP Publication 27, the average years of life lost from radiation-induced cancer death was estimated to be 10-15 years (88), while others have estimated it as 14-15 years (15,87,89). To the best of the author's knowledge, only a couple of publications have employed this type of conversion method (61,75). A problem is that this conversion method also assumes an instant consequence of the risk. The only alteration is that the population exposed to the risk has now been interpreted to have an average of 10-15 or 14-15 years left to live.

To take into account the time that passes between exposure to ionising radiation and the risk of radiation-induced cancer, Mubayi et al. (90) applied a discount rate (DR) in their conversion method, which was published in 1995. In health economics, a DR is applied to consider that a benefit to be received in the future is worth less compared to receiving the same benefit today (6,49,91,92). According to the Ramsey rule (6,92), there are two main reasons for this: (i) people are impatient (preferring advantages now rather than later) and (ii) societies often grow richer over time, meaning that future consumption has a lower utility. Equation 3 can be applied to convert the value of a future benefit *B* into its present value *pv*:

$$pv = \frac{B}{(1 + DR)^t} \qquad \text{Equation 3}$$

where *t* denotes time, usually expressed in years (49,93,94). Developments of the conversion method published by Mubayi et al. (90) in 1995 can be found thanks to recent advances within health economics and radiological protection. For example, minor updates of their presented exposure risk and DR recommendation can be applied. Mubayi et al. (90) used a latency period (the minimum time between exposure and cancer diagnosis) of either 2, 5 or 10 years for different cancer sites. A more appropriate estimation would be the median number of years between exposure to ionising radiation and cancer diagnosis (NYEC). In the search for the NYEC, one of the specific aims of this thesis was (as presented in Paper II p.2): ‘to develop a new conversion method on how to convert societal costs into an α value’.

2.7 QUALITATIVE APPROACHES IN THE DECISION-MAKING PROCESS

As mentioned in Section 2.1, quantitative DATs should only be seen as one of several inputs to the decision-making process. According to the ICRP, the optimisation process should be viewed more broadly and incorporate qualitative approaches such as individual equity, safety culture and stakeholder involvement (10).

Individual equity mainly refers to the point where individual doses should be considered in the optimisation process and it is closely linked to the core ethical value of justice (9,10). In a scenario where two protection options yield the same collective dose, the preferable option is the one with the most individual equity in exposure distribution (10). A collective dose that has been measured in a large population can provide misleading information because of a lack of homogeneity in exposure distribution. A solution to this problem is to divide the population into smaller groups with more homogeneous exposure distributions (10).

A strong safety culture supports a high-quality optimisation process. It is the responsibility of the operating management to ensure that a strong safety culture is developed and maintained by both staff and management (10). This is often achieved by the implementation of policies and quality assurance programmes. The role of an inspecting authority is to evaluate processes, procedures, and judgements, rather than to concentrate on the specific outcomes of the optimisation process (10). The ability of an authority to encourage an operating management to improve their optimisation processes and safety culture is dependent on a productive dialogue. Finally, it should be stressed that the operating management makes the final decisions about a process, therefore the burden of proof of an optimised process is also their responsibility (10).

Stakeholder involvement is seen as an essential aspect of the optimisation process and closely linked to the core ethical value of dignity (4,9,10,36). The term ‘stakeholder’ broadly refers to all parties that have an interest in or concern about an exposure scenario. For example, stakeholders may include the general public or workers exposed to risks, environmental organisations, representative unions, authorities or policymakers. Stakeholder involvement has many proven benefits (10). It can facilitate the creation of sustainable decisions by incorporating a broad value perspective. It can also help to resolve conflicts caused by competing interests as well as building trust in authorities and companies. Furthermore, stakeholder involvement can facilitate the identification of radiological protection options and assessment of their advantages and disadvantages. Stakeholder involvement is important in complex optimisation processes. However, many decisions within radiological protection are straightforward and non-controversial. In these decisions, the need for stakeholder involvement is limited. Finally, the concept of stakeholder involvement does not lessen the operating management’s accountability for making the final decisions regarding optimisation of radiological protection (10).

In 2022, Wieder et al. (16) proposed the three R’s of ‘reasonableness’ within radiological protection as: Relationships (stakeholders, empathy and trust), Rationale (contextual, technical and ethical) and Resources (technological, financial and time). This framework (or checklist) was suggested as a guide for radiation protection experts when working with the concept of reasonableness within the ALARA principle. Moreover, the framework is described as a ‘deliberative information gathering and sharing approach’ (16 p.5–6). This thesis touches upon most of the themes of the three R’s of reasonableness but mainly focuses on resources (financial) and relationships (stakeholders). Papers I, II and III all provides α-value recommendations, which are useful in

DATs such as CBA. Thus, the contribution of these papers pertains to the theme of resources (financial). Wieder et al. (16) further point out that while quantitative DATs contribute to the optimisation process, it is often challenging to quantify moral and human values. Therefore, they stress the importance of qualitative aspects such as professional judgments in the determination of reasonableness. Regarding the relationship theme (stakeholders), Wieder et al. (16) acknowledge that radiation protection experts cannot identify the perspectives of each and every stakeholders without external input. An exposure scenario that is considered tolerable by one community can be unacceptable to another. Furthermore, Wieder et al. (16) stress that public opinion can sometimes influence decision-makers more than the opinion of radiation protection experts. The recommended α values provided in Papers I and II are based on general VSL estimates derived from surveys of the stated preference approach. In these surveys, questions were asked about the general public's WTP to avoid a small risk of death in the context of environmental, health or transport risks. In this way, stakeholders (the general public) were involved in determining how much of their society's financial resources should be spent on avoiding risks in general, and in this case the findings have been implemented within radiological protection through the benefit transfer approach. In Paper III, staff members exposed to ionising radiation at their workplace in Region Västra Götaland (Sweden) took part in a stated preference approach survey. Among other questions, they were asked about their WTA compensation for being exposed to a small risk of radiation-induced cancer death at their workplace. Thus, the α value provided in Paper III can be seen as a very direct stakeholder involvement. In this framework, the qualitative approach of stakeholder involvement was merged with a quantitative DAT. Paper IV is also based on a high degree of stakeholder involvement, as it investigates staff members' experience of discomfort associated with wearing lead aprons and thyroid collars for long periods of time. Moreover, Paper IV also explores staff members' willingness to tolerate a small increase in future cancer risk in order to avoid wearing these protective tools. The results of Paper IV identify some of the obstacles in making reasonable decisions about the use of lead aprons and thyroid collars in scenarios where staff exposure can be considered minimal.

2.8 LEAD APRONS AND THYROID COLLARS

Lead aprons were introduced as a protective tool shortly after the discovery of X-rays (95). In 1935, only 60% of radiographers in the U.S. used lead aprons, but in 1970 that proportion had increased to 97% (96). The use of thyroid collars has increased in recent decades, from 47% in the early 1990s to around 94% in the early 2010s (97–99). A lead apron is estimated to provide an effective dose reduction of 75%-97% for staff working in an operating or angiography theatre (100,101). A thyroid collar is estimated to provide an additional dose reduction of approximately 50% compared with the use of a lead apron alone (98,102).

Lead aprons and thyroid collars are also related to disadvantages such as fatigue and an increased risk of back pain (103). By means of an infrared camera, Alexandre et al. (104) reported an increased skin temperature in staff working with lead aprons compared to staff who did not wear them. Their conclusion was that the higher skin temperature is a result of greater muscular activity, experienced by staff as warmth and fatigue. Furthermore, several studies have reported an association between back pain and wearing lead aprons for long periods of time (97,105–112). Therefore, a couple of solutions have been developed to mitigate this problem, such as lead aprons that are ceiling-suspended (113) and lead aprons that are 20% lighter (consisting of tungsten and tin instead of lead) (114). Although modern radiation protection aprons no longer contain lead, the term ‘lead apron’ remains widely used and is therefore also adopted in this thesis.

The use of lead aprons and thyroid collars should also be seen in the context of the decreased occupational exposure that has been reported (96,115–117). Among 88,000 radiographers in the U.S., a decline of 92% in badge doses has been reported between the 1950s and the 1970s (96). In a more recent example (between 1989 and 2004), Vano et al. (116) found a decrease in occupational exposure for interventional cardiologists in Spain from an annual average of 11.2 mSv to 1.2 mSv. These days, anaesthesia personnel have been reported to wear lead aprons even when their exposure without them (in certain procedures) is measured to be only a few µSv (118–121).

In this context, it is important to ask oneself the question: How safe is safe enough? Mori et al. (122) touched upon this question when stating that the recommendation for interventional cardiologists should be to wear lead aprons of 0.25 mm instead of 0.5 mm lead thickness. Even though the thicker (and heavier) lead apron (0.5 mm) provides an additional effective dose reduction of 2.2 mSv per year compared to the thinner lead apron (0.25 mm), they were more concerned about the increased risk of back pain associated with carrying a heavy load. Moreover, Huda and Boutcher (123) provided an efficiency parameter, where the effective dose reduction of wearing a lead apron within a nuclear medicine department was divided by the time spent wearing it. They highlighted the subjective component of balancing the effective dose reduction with the strain of carrying the weight of a lead apron. Their conclusion was that the ALARA principle has an admirable purpose, but it can sometimes be problematic to work with. This conclusion inspired one of the specific aims of this thesis (as presented in Paper IV p.2): ‘to investigate staff’s experience of discomfort associated with wearing lead aprons and thyroid collars for long periods of time, and also to investigate staff’s willingness to tolerate personal dose equivalent (expressed as radiation dose) and the corresponding increase in future cancer risk to avoid wearing these protective tools’.

3 AIM

With a primary focus on occupational radiological protection, the overall aim of this thesis was to answer the question: How safe is safe enough? To fulfil the overall aim, four specific aims were formulated, of which aims 2, 3, and 4 correspond directly to those presented in the individual papers:

1. To develop new α-value recommendations applicable to occupational radiological protection (as presented in Papers I, II and III).
2. To describe cases of CBAs in occupational radiological protection within the Swedish healthcare system (as presented in Paper I).
3. To develop a new conversion method on how to convert societal costs into an α value (as presented in Paper II).
4. To investigate staff's experience of discomfort associated with wearing lead aprons and thyroid collars for long periods of time, and also to investigate staff's willingness to tolerate personal dose equivalent (expressed as radiation dose) and the corresponding increase in future cancer risk to avoid wearing these protective tools (as presented in Paper IV).

4 SUMMARY OF PAPERS

This section is structured in line with the four specific aims of the thesis, starting with the methods and results of the recommended α values presented in Papers I, II and III. Thereafter, CBA cases in occupational radiological protection within the Swedish healthcare system are described (Paper I). Furthermore, in Paper II a new method for converting societal costs into an α value is provided. Finally, the methods and results of Paper IV about stakeholder involvement in the use of lead aprons and thyroid collars for long periods of time are reported. This section (Methods and Results) also includes discussion of certain findings from the papers, whereas Section 5 (Discussion) provides a broader perspective on the research field in a more general context.

4.1 ALPHA-VALUE RECOMMENDATIONS

Papers I, II and III each provide α-value recommendations based on different health economics techniques and assumptions. For example, Papers I and II employ the benefit transfer method (described in Section 2.5), while Paper III is based on a survey of the risk context of interest. Thus, the results from these recommendations also diverge. Below, the methods and results of the different α-value recommendations are presented one by one and also compared with each other.

4.1.1 PAPER I

One of the two aims of Paper I (p.297) was: ‘to compare examples within health economics used by authorities and institutes in Sweden, and by these examples calculate corresponding α values for radiation protection purposes’. This aim refers to the benefit transfer method, meaning that VSL estimates from other risk contexts can be transferred to the specific risk context of interest (in this case occupational radiological protection). The strength of this method is that financial resources will be equally distributed between risk contexts.

Recommendations from three Swedish authorities and institutes about two concepts within health economics were applied in Paper I. The first concept was VSL, which is described in detail in Section 2.5. The second concept was a quality-adjusted life year (QALY). The price of one QALY is described as the value of one person living for one year with perfect health (49). The concept is often applied within the healthcare system to evaluate new drugs compared to present alternatives (124). Persson and Hjelmgren (125) investigated how to convert the price of a QALY into a VSL (and vice versa) by considering a number of factors. These factors comprise the mean number of years of life lost through traffic accidents, the quality of life, the excess burden of taxes and the use of a DR. They concluded (in their specific context of traffic accidents) that a VSL can be calculated by multiplying a factor of 24.8 by the estimated price of a QALY.

In Paper I, the conversion method published in 1995 by Mubayi et al. (90) was used to convert recommended VSLs from Swedish authorities and institutes into α-value recommendations. In this conversion method, Mubayi et al. (90) applied exposure risk factors for nine different cancer sites, considering both fatal and non-fatal cases. They also provided estimates of the healthcare costs for these nine cancer sites. Moreover, they applied a latency period of 2 years for leukaemia and bone cancer, 5 years for thyroid cancer and 10 years for breast cancer, lung cancer, gastro-intestinal cancer, benign cancer, skin cancer and other cancer sites. Mubayi et al. (90) used these latency periods to discount both the given VSLs and the healthcare costs. They provided calculations with DRs of either 3% or 7%. The Swedish Civil Contingencies Agency (49) recommends a DR of 3%, which was therefore applied in Paper I. According to Mubayi et al. (90), a VSL of $3 million, combined with the presented healthcare costs and a DR of 3%, can be converted into an α value of $122 per man·mSv. This means that a VSL (expressed in millions of USD) can be converted into an α value (expressed in USD per man·mSv) by multiplying the VSL by a factor of 40.7, a proportionality also suggested by Mubayi et al. (90).

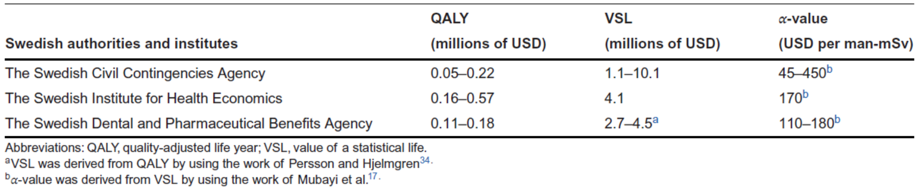
Focusing on QALYs and VSLs, a comparison of key recommendations from three Swedish authorities and institutes was presented in Paper I:

1. The Swedish Civil Contingencies Agency has published a report (49) stating that the price of a QALY in 2012 was between 0.45 and 1.95 million SEK and that the VSL in 2012 was between 10 and 100 million SEK. In Paper I, these figures were converted into $0.05-$0.22 million for a QALY and $1.1-11.0 million for a VSL, now in 2021 USD. The VSLs provided by The Swedish Civil Contingencies Agency are based on an empirical literature review by Hultkrantz and Svensson (43), where most references are from studies of the stated preference approach in the context of traffic accidents.

2. The Swedish Institute for Health Economics has studied the Swedish general public's WTP for decreasing their own risk of being injured or killed in a traffic accident (72). They reported the price of a QALY in 2016 to be between 1.5 and 5.3 million SEK and the VSL to be 38 million SEK. In Paper I, these figures were converted into 2021 USD and presented as \$0.16-\$0.57 million for a QALY and \$4.1 million for a VSL. The Swedish Transport Administration (94,126) has made similar recommendations about VSLs, which in turn are based on the report by the Swedish Institute for Health Economics (72) and the empirical literature review by Hultkrantz and Svensson (43).
3. It has been shown that The Swedish Dental and Pharmaceutical Benefits Agency applies a limit between 0.7 and 1.2 million (2011 SEK) for the price of a QALY when accepting a new drug in the national pharmaceutical benefits scheme (124). In Paper I, this price was reported as \$0.11-\$0.18 million per QALY (2021 USD). For comparison with the recommended VSLs from the other two Swedish authorities and institutes, this price of a QALY was converted into a VSL by the factor of 24.8 (as described above), thus representing a VSL of \$2.7-\$4.5 million.

In Paper I, these key recommendations related to QALYs and VSLs from three Swedish authorities and institutes were presented along with corresponding calculated α values. As described above, the conversion method provided by Mubayi et al. (90) was used in Paper I, that is, a multiplication of 40.7 between a VSL and an α value. These figures are reproduced in Table 3.

Table 3. Comparison of key references pertaining to QALYs and VSLs from three Swedish authorities and institutes and calculated α values (2021 USD). This table is reproduced from: 'A case study of cost-benefit analysis in occupational radiological protection within the healthcare system of Sweden' by Engström et al. (Paper I), J Appl Clin Med Phys, 2021;22(10):295-304, licensed under CC BY 4.0 (2).

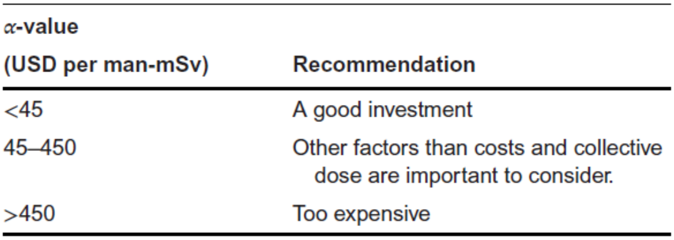


Swedish authorities and institutes	QALY (millions of USD)	VSL (millions of USD)	α-value (USD per man-mSv)
The Swedish Civil Contingencies Agency	0.05–0.22	1.1–10.1	45–450[b]
The Swedish Institute for Health Economics	0.16–0.57	4.1	170[b]
The Swedish Dental and Pharmaceutical Benefits Agency	0.11–0.18	2.7–4.5[a]	110–180[b]

Abbreviations: QALY, quality-adjusted life year; VSL, value of a statistical life.
[a] VSL was derived from QALY by using the work of Persson and Hjelmgren[34].
[b] α-value was derived from VSL by using the work of Mubayi et al.[17].

The uncertainties in estimating VSLs are evident in the recommendation provided by The Swedish Civil Contingencies Agency, given as an interval with a factor of 10 between low and high. This interval (\$1.1-\$11.0 million) encompasses the recommended VSLs from the other two Swedish authorities and institutes (see Table 3). Therefore, it was concluded in Paper I that this interval of VSLs (from the Swedish Civil Contingencies Agency) would be useful for conversion into an α-value recommendation, also presented as an interval. Croft and Lochard (127) have suggested the use of a 'band scheme' to interpret the uncertainties in the determination of an α value. In this band scheme an interval of possible α values was divided into three groups: (i) below the interval was considered a good investment, (ii) within the interval, it was important to consider factors other than cost and collective dose and (iii) above the interval was considered too expensive. With this band scheme in mind, an α-value recommendation (in 2021 USD) was provided in Paper I, presented here in Table 4.

Table 4. Recommended α values (2021 USD) applicable to occupational radiological protection in Sweden. This table is reproduced from: 'A case study of cost-benefit analysis in occupational radiological protection within the healthcare system of Sweden' by Engström et al. (Paper I), J Appl Clin Med Phys, 2021;22(10):295-304, licensed under CC BY 4.0 (2).



α-value (USD per man-mSv)	Recommendation
<45	A good investment
45–450	Other factors than costs and collective dose are important to consider.
>450	Too expensive

4.1.2 PAPER II

One of the two aims in Paper II (p.2) was: 'to provide recommendations of α values (for both the public and workers) for each member country of The Organisation for Economic Co-operation and Development (OECD)'. The benefit transfer method was applied in Paper II and the recommended α values were based on societal costs consisting of a general VSL, productivity losses and healthcare costs.

In Paper II, a general VSL estimate (64) based on environmental, health and transport risks was used. This VSL estimate of $1.5-4.5 million (2005 USD) was provided by OECD as one of several meta-analyses on this topic (43,63,65,128–138). Banzhaf (139) even published a meta-analysis of other meta-analyses of VSL estimates (for the U.S.). The meta-analysis published by the OECD (64) was based on 77 studies of the stated preference approach and contained a total of 856 VSL estimates. The OECD decided to apply a transfer error of ±50% in their meta-analysis, therefore presenting their recommended VSL estimate as an interval. Most published studies of the stated preference approach are based on the WTP of the general public to avoid a small risk of death (43,64). In Paper III, it was reported that workers exposed to ionising radiation in the Swedish healthcare system generally have 7% more QALYs to live compared to the Swedish general public, due to differences in age, sex and overall self-rated health. To account for this variation in population characteristics in Paper II, the recommended VSL estimates from the OECD (64) were increased by a factor of 1.07 for workers. General VSL estimates (adjusted for time and country) in Paper II are reported as intervals between VSL_{min} and VSL_{max} for each OECD member state in Table 5 for the general public and in Table 6 for workers.

Productivity losses from premature cancer deaths have been studied by means of the human capital approach (140). In the human capital approach, the years of potential working life lost due to premature cancer deaths are multiplied by annual earnings and thereafter totalled and discounted to present values. In Paper II, three different studies (Luengo-Fernandez et al. (141), Hofmarcher et al. (142), and Hanly et al. (143)) were used, all of which reported on productivity losses from general premature cancer deaths. Each of these studies reported on productivity losses from multiple European countries, including about 65% of the member states of the OECD. To consider disparities between general premature cancer deaths and premature radiation-induced cancer deaths (in Paper II), the years of potential working life lost from radiation-induced cancer death were assessed by Monte Carlo simulations. Based on the findings of these simulations, a mean of 7.6 years of working life is lost due to radiation-induced cancer deaths for the general public, whereas the corresponding mean for workers is 5.4 years. This difference reflects variations in the age distribution between the two populations. Consequently, productivity losses among workers were estimated to be 29% lower than in the general public. The Monte Carlo simulations underlying these estimates are described in more detail in Section 4.3.3. The productivity losses from premature radiation-induced cancer deaths adjusted for time and country are shown in Table 5 for the general public and in Table 6 for workers. It is revealed that productivity losses are small (2-6%) compared to estimated VSLs.

Healthcare costs from diagnosis to end of life for several different cancer sites can only be found in a few studies (144–148). Of these, the outcomes of the two most recent publications (de Oliveira et al. (147) and Wu et al. (148)) were applied in Paper II. In 2016, de Oliveira et al. (147) identified lifetime cancer costs in Canada from 21 different cancer sites. They examined costs during different phases of the disease (pre-diagnosis, initial, continuing, terminal) and followed patients for up to 25 years after diagnosis. In 2018, Wu et al. (148) investigated lifetime cancer costs in Taiwan from 19 different cancer sites, following up patients 17 years after diagnosis. In Paper II, healthcare costs were assumed to be the same for both the general public and workers that are diagnosed with cancer. These healthcare costs were adjusted for time and country and are presented in Tables 5 and 6. It emerged that the healthcare costs are also small (0-3%) compared to estimated VSLs. A similar outcome has also been reported by others (64,90).

Economic adjustments of societal costs for both time and economic deviations between countries were applied in Paper II with the help of a methodology presented by the OECD (64). Regarding VSL time adjustments, these were made by applying Equation 4:

$$VSL_{present} = VSL_{past} \cdot \left(\frac{CPI_{present}}{CPI_{past}}\right) \cdot \left(\frac{AIC_{present}}{AIC_{past}}\right)^{0.8} \qquad \text{Equation 4}$$

where *CPI* is the consumer price index (149) and *AIC* is the actual individual consumption per capita (constant purchasing power parities) (150). If the actual individual consumption per capita was not accessible, a second-best estimate was used, namely the gross domestic product per capita. The OECD recommends applying an income elasticity of 0.8 to take account of the fact that people’s WTP to avoid a small risk of death is not strictly proportional to their income (64). In Paper II, VSLs were adjusted for economic deviations between countries, also using actual individual consumption per capita with an income elasticity of 0.8. Productivity losses and healthcare costs were likewise adjusted on the basis of actual individual consumption per capita, but without applying the income elasticity factor. Countries’ expenditure on healthcare costs as a proportion of their gross domestic product was also considered in these adjustments (151).

The three types of societal costs (general VSL, productivity losses and healthcare costs) were converted into an α value by means of the conversion method developed in Paper II (see Section 4.3). The recommended α values for Sweden were presented (in Paper II) as \$57-171 per man·mSv for the general public and \$62-163 per man·mSv for workers (2023 USD). Most countries within the OECD have a comparable economic situation and were therefore also provided with similar α-value recommendations in Paper II. However, there were also differences. For example, the recommended α values for the general public in Mexico were \$31-93 per man·mSv, compared with \$80-242 per man·mSv for the general public in the U.S. (2023 USD). In Paper II, intervals of α-value recommendations for each OECD member state were presented and are here reproduced in Table 7. These intervals should be interpreted with the same band scheme as described in Section 4.1.1. Finally, it should be noted that planned exposure of the general public is regarded as involuntary, in contrast to planned exposure of workers. This disparity in voluntariness is reflected in the ICRP dose limits: an effective dose limit of 1 mSv per year for the general public, compared to 20 mSv per year for workers, whose effective dose is averaged over five years with a maximum of 50 mSv in any single year (4). Regarding planned exposure situations, the α-values recommended in Paper II are applicable below these dose limits, hence no further consideration of the difference in voluntariness between the general public and workers was deemed necessary.

Table 5. For the general public, estimates of general VSLs, productivity losses and healthcare costs for each OECD member state (2023 USD millions). This table is built upon the work: ‘How much resources are reasonable to spend on radiological protection?’ by Engström et al. (Paper II), J Radiol Prot, 2024;44(4):041516, licensed under CC BY 4.0 (2).

	General VSL		Productivity losses			Healthcare costs	
Country	OECD (64) VSL_{min}	OECD (64) VSL_{max}	Luengo-Fernandez et al. (141)	Hofmarcher et al. (142)	Hanly et al. (143)	de Oliveira et al. (147)	Wu et al. (148)
Australia	3.2	9.5	0.39	0.29	0.25	0.075	0.13
Austria	2.8	8.3	0.39	0.27	0.22	0.087	0.15
Belgium	2.8	8.4	0.36	0.27	0.22	0.076	0.13
Canada	2.9	8.7	0.36	0.28	0.22	0.078	0.14
Chile	2.0	6.0	0.17	0.14	0.11	0.031	0.054
Colombia	1.6	4.9	0.10	0.10	0.08	0.020	0.036
Costa Rica	1.9	5.6	0.15	0.13	0.11	0.020	0.039
Czech Republic	2.2	6.5	0.25	0.20	0.17	0.044	0.074
Denmark	2.8	8.3	0.37	0.27	0.23	0.067	0.12
Estonia	2.2	6.6	0.19	0.17	0.16	0.026	0.047
Finland	2.8	8.3	0.36	0.26	0.22	0.070	0.12
France	2.7	8.1	0.35	0.25	0.21	0.081	0.14
Germany	2.9	8.6	0.37	0.28	0.24	0.091	0.16
Greece	1.8	5.4	0.33	0.18	0.15	0.055	0.070
Hungary	1.8	5.4	0.20	0.16	0.14	0.025	0.042
Iceland	2.7	8.0	0.36	0.29	0.25	0.060	0.10
Ireland	2.4	7.1	0.31	0.23	0.19	0.037	0.059
Israel	2.4	7.2	0.24	0.20	0.16	0.035	0.062
Italy	2.2	6.5	0.34	0.23	0.18	0.058	0.092
Japan	2.7	8.1	0.34	0.25	0.21	0.075	0.13
Korea	2.6	7.7	0.24	0.20	0.17	0.044	0.081

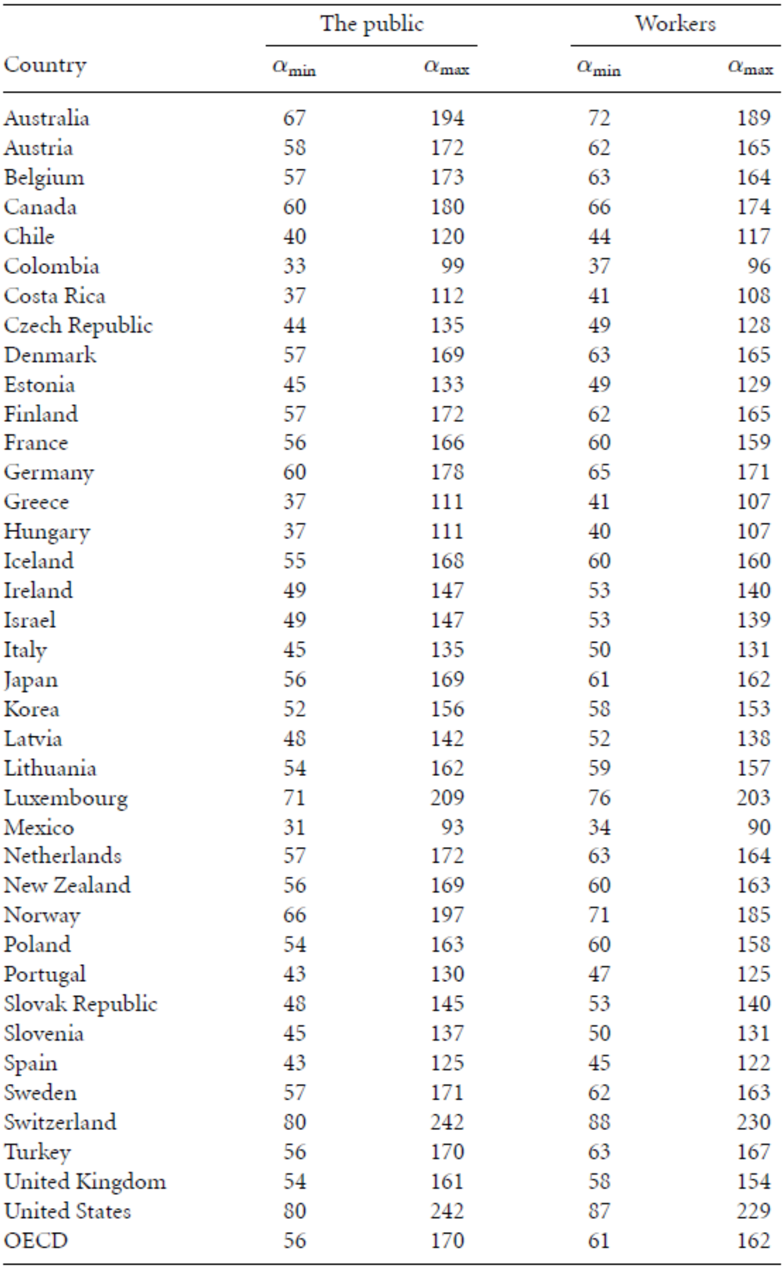
Latvia	2.3	7.0	0.17	0.16	0.14	0.029	0.058
Lithuania	2.7	8.0	0.22	0.21	0.18	0.032	0.060
Luxembourg	3.4	10	0.49	0.35	0.28	0.052	0.087
Mexico	1.5	4.6	0.17	0.13	0.10	0.018	0.033
Netherlands	2.8	8.3	0.39	0.27	0.22	0.083	0.14
New Zealand	2.7	8.2	0.30	0.24	0.21	0.065	0.12
Norway	3.1	9.4	0.40	0.30	0.24	0.061	0.11
Poland	2.7	8.1	0.22	0.19	0.17	0.028	0.049
Portugal	2.1	6.3	0.28	0.20	0.17	0.057	0.088
Slovak Republic	2.4	7.2	0.24	0.18	0.16	0.035	0.057
Slovenia	2.2	6.7	0.26	0.19	0.16	0.043	0.069
Spain	2.0	6.1	0.31	0.21	0.17	0.062	0.095
Sweden	2.8	8.3	0.36	0.27	0.22	0.074	0.13
Switzerland	3.9	12	0.55	0.39	0.33	0.12	0.23
Turkey	2.9	8.6	0.15	0.15	0.13	0.013	0.027
United Kingdom	2.6	7.8	0.35	0.27	0.20	0.077	0.13
United States	3.8	12	0.50	0.38	0.33	0.16	0.27
OECD	2.7	8.2	0.33	0.25	0.21	0.059	0.10

Table 6. For workers, estimates of general VSLs, productivity losses and healthcare costs for each OECD member state (2023 USD millions).

	General VSL		Productivity losses			Healthcare costs	
Country	OECD (64) VSL_{min}	OECD (64) VSL_{max}	Luengo-Fernandez et al. (141)	Hofmarcher et al. (142)	Hanly et al. (143)	de Oliveira et al. (147)	Wu et al. (148)
Australia	3.4	10	0.28	0.21	0.18	0.075	0.13
Austria	3.0	8.9	0.28	0.20	0.16	0.087	0.15
Belgium	3.0	9.0	0.26	0.19	0.16	0.076	0.13
Canada	3.1	9.3	0.26	0.20	0.16	0.078	0.14
Chile	2.1	6.4	0.12	0.10	0.08	0.031	0.054
Colombia	1.8	5.3	0.07	0.07	0.06	0.020	0.036
Costa Rica	2.0	6.0	0.11	0.09	0.08	0.020	0.039
Czech Republic	2.3	7.0	0.18	0.14	0.12	0.044	0.074
Denmark	3.0	8.9	0.26	0.19	0.17	0.067	0.12
Estonia	2.4	7.1	0.14	0.12	0.11	0.026	0.047
Finland	3.0	8.9	0.26	0.19	0.16	0.070	0.12
France	2.9	8.6	0.25	0.18	0.15	0.081	0.14
Germany	3.1	9.2	0.27	0.20	0.17	0.091	0.16
Greece	1.9	5.8	0.24	0.13	0.11	0.055	0.070
Hungary	1.9	5.8	0.14	0.11	0.10	0.025	0.042
Iceland	2.9	8.6	0.26	0.21	0.18	0.060	0.10
Ireland	2.5	7.6	0.23	0.16	0.13	0.037	0.059
Israel	2.6	7.7	0.17	0.14	0.12	0.035	0.062
Italy	2.3	7.0	0.24	0.16	0.13	0.058	0.092
Japan	2.9	8.7	0.24	0.18	0.15	0.075	0.13
Korea	2.8	8.3	0.17	0.14	0.12	0.044	0.081
Latvia	2.5	7.5	0.12	0.12	0.10	0.029	0.058
Lithuania	2.9	8.6	0.16	0.15	0.13	0.032	0.060

Luxembourg	3.6	11	0.35	0.25	0.20	0.052	0.087
Mexico	1.6	4.9	0.12	0.09	0.07	0.018	0.033
Netherlands	3.0	8.9	0.28	0.19	0.16	0.083	0.14
New Zealand	2.9	8.8	0.21	0.17	0.15	0.065	0.12
Norway	3.4	10	0.28	0.21	0.17	0.061	0.11
Poland	2.9	8.6	0.16	0.14	0.12	0.028	0.049
Portugal	2.2	6.7	0.20	0.14	0.12	0.057	0.088
Slovak Republic	2.6	7.7	0.17	0.13	0.12	0.035	0.057
Slovenia	2.4	7.1	0.18	0.13	0.11	0.043	0.069
Spain	2.2	6.5	0.22	0.15	0.12	0.062	0.095
Sweden	3.0	8.9	0.26	0.19	0.16	0.074	0.13
Switzerland	4.1	12	0.39	0.28	0.23	0.12	0.23
Turkey	3.1	9.2	0.11	0.11	0.10	0.013	0.027
United Kingdom	2.8	8.4	0.25	0.19	0.15	0.077	0.13
United States	4.1	12	0.35	0.27	0.23	0.16	0.27
OECD	2.9	8.8	0.24	0.18	0.15	0.059	0.10

Table 7. Recommended α values for each OECD member state, provided as intervals between α_{min} and α_{max} [2023 USD per man·mSv]. This table is reproduced from: 'How much resources are reasonable to spend on radiological protection?' by Engström et al. (Paper II), J Radiol Prot, 2024;44(4):041516, licensed under CC BY 4.0 (2).



Country	The public		Workers	
	α_{min}	α_{max}	α_{min}	α_{max}
Australia	67	194	72	189
Austria	58	172	62	165
Belgium	57	173	63	164
Canada	60	180	66	174
Chile	40	120	44	117
Colombia	33	99	37	96
Costa Rica	37	112	41	108
Czech Republic	44	135	49	128
Denmark	57	169	63	165
Estonia	45	133	49	129
Finland	57	172	62	165
France	56	166	60	159
Germany	60	178	65	171
Greece	37	111	41	107
Hungary	37	111	40	107
Iceland	55	168	60	160
Ireland	49	147	53	140
Israel	49	147	53	139
Italy	45	135	50	131
Japan	56	169	61	162
Korea	52	156	58	153
Latvia	48	142	52	138
Lithuania	54	162	59	157
Luxembourg	71	209	76	203
Mexico	31	93	34	90
Netherlands	57	172	63	164
New Zealand	56	169	60	163
Norway	66	197	71	185
Poland	54	163	60	158
Portugal	43	130	47	125
Slovak Republic	48	145	53	140
Slovenia	45	137	50	131
Spain	43	125	45	122
Sweden	57	171	62	163
Switzerland	80	242	88	230
Turkey	56	170	63	167
United Kingdom	54	161	58	154
United States	80	242	87	229
OECD	56	170	61	162

4.1.3 PAPER III

In contrast to Papers I and II (based on the benefit transfer method), Paper III was based on a survey of the risk context of interest (occupational radiological protection). Hence, Paper III should be seen in the light of the ICRP's recommendation about stakeholder involvement as an important part of the optimisation process (10), which was described in more detail in Section 2.7 of this thesis. The aim of Paper III (p.570) was: 'to estimate an α value useful for occupational radiological protection within the healthcare system of Sweden'.

In Paper III, a survey was sent by email to a total of 4,680 workers exposed to ionising radiation at their workplace in Region Västra Götaland (Sweden), of whom 718 replied, a response rate of 15%. In the survey, the respondents were presented with two fictitious scenarios. In the first scenario, they were asked about their WTP for measures against radon exposure in their home. They were told to assume that they were living alone and had bought a new house with elevated radon levels. Without protective action, the risk of dying from radiation-induced cancer one or several decades after relocating to the new house was presented as 40 out of 100,000 (0.04%). With protective action, the same risk would be halved to 20 out of 100,000 (0.02%). It should be noted that there is no need to discount the respondents' WTP, because the future aspect of radiation-induced cancer has already been included in the scenario as 'one or several decades after relocating to the new house' (author's translation). In the second scenario, the respondents were asked about their WTA getting compensated for radiation exposure from X-ray machines at their workplace. They were now required to assume that the hospital where they worked had bought two new X-ray machine models: one low-cost model (A) with higher exposure for staff and one more expensive model (B) with lower exposure for staff. The staff were then offered different levels of a lump sum (a form of compensation) for agreeing to work with the low-cost model A.

It is difficult for respondents to answer these types of question out of the blue (in both of the scenarios), which can result in many outliers (152). Therefore, to help the respondents in Paper III, they were asked about their WTP and WTA by applying the payment card method (152), meaning that they were required to take a position (yes, uncertain or no) for a number of proposed values ($1, $10, $100, $1,000, $10,000, $100,000). Thereafter, they were asked to state their WTP and WTA in an open-ended question. Both scenarios (in Paper III) were then repeated but with additional risk reductions presented.

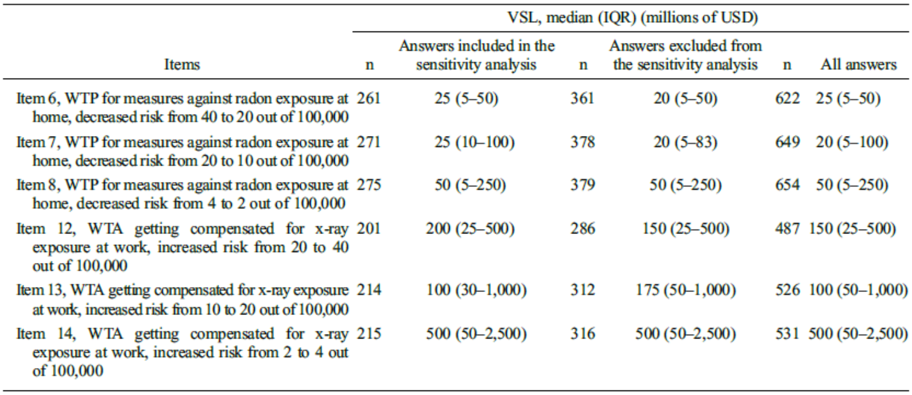
This approach was used to try to compensate for respondents' scale-insensitivity. This is because respondents are often not proportional in terms of their WTP and WTA in relation to the magnitude of the presented risk reductions (69–72). Moreover, respondents in Paper III whose answers could be considered irrational, such as those who increased their WTP or WTA throughout the survey even though the presented risk reduction actually decreased, were excluded in the sensitivity analysis. Another shortcoming of the stated preference approach is hypothetical bias, meaning that respondents sometimes overestimate their WTP in surveys compared to their true WTP in real-life situations (67–69). Certainty questions have been suggested in an attempt to overcome this problem (72,153–155). Respondents are asked to rate their certainty (on a scale of 1 to 10) that they would truly pay the amount specified in the survey if confronted with a real-life situation. Loomis et al. (155) have recommended that answers of less than seven should be excluded in sensitivity analyses. This approach was applied in Paper III.

Olofsson et al. (72) have suggested the use of so-called control questions to identify respondents who 'protest' against the given fictitious scenario, in order to exclude their answers in a sensitivity analysis. One of the control questions in Paper III required the respondents to explain if they had answered $0 in either of the two scenarios. One example (from Paper III p.571) of such a 'protest' answer was: 'I think that the government should pay for protective actions against radon'. In Paper III, a sensitivity analysis was performed to exclude answers for various reasons. For one of the open-ended questions about radon (given here as an example) 622 answers were received. Of those:

- 16 were excluded as irrational (an increasing WTP or WTA throughout the survey despite decreasing risk reduction),
- 316 were excluded based on the certainty question (a score below seven) and
- 29 were excluded as 'protest' answers.

The contingent valuation method of the stated preference approach (43,72) was used in Paper III, where the given WTP and WTA were divided by the risk reduction of the question, in order to present the respondents' VSLs for the given context. Using this method, the respondents' answers relating to VSLs from the six open questions with different risk reductions, based on the two scenarios (WTP to avoid exposure from radon and WTA compensation for exposure from X-ray machines), were presented in Paper III. These answers are reproduced in Table 8, where they are also divided into those included and those excluded in the sensitivity analysis.

Table 8. The respondents' answers relating to VSLs from the six open questions with different risk reductions (questions 6, 7 and 8 about radon and questions 12, 13 and 14 about X-ray machines). VSLs are presented as the median (interquartile range) [millions of USD], and (n) represents the number of answers for each question. This table is reproduced from: 'An Estimation of the Monetary Value of the Person-Sievert Useful for Occupational Radiological Protection within the Healthcare System of Sweden' by Engström et al. (Paper III), Health Phys. 2024;127(5):569-580, licensed under CC BY-NC-ND 4.0 (2).



	VSL, median (IQR) (millions of USD)					
Items	n	Answers included in the sensitivity analysis	n	Answers excluded from the sensitivity analysis	n	All answers
Item 6, WTP for measures against radon exposure at home, decreased risk from 40 to 20 out of 100,000	261	25 (5–50)	361	20 (5–50)	622	25 (5–50)
Item 7, WTP for measures against radon exposure at home, decreased risk from 20 to 10 out of 100,000	271	25 (10–100)	378	20 (5–83)	649	20 (5–100)
Item 8, WTP for measures against radon exposure at home, decreased risk from 4 to 2 out of 100,000	275	50 (5–250)	379	50 (5–250)	654	50 (5–250)
Item 12, WTA getting compensated for x-ray exposure at work, increased risk from 20 to 40 out of 100,000	201	200 (25–500)	286	150 (25–500)	487	150 (25–500)
Item 13, WTA getting compensated for x-ray exposure at work, increased risk from 10 to 20 out of 100,000	214	100 (30–1,000)	312	175 (50–1,000)	526	100 (50–1,000)
Item 14, WTA getting compensated for x-ray exposure at work, increased risk from 2 to 4 out of 100,000	215	500 (50–2,500)	316	500 (50–2,500)	531	500 (50–2,500)

As can be seen in Table 8, the VSLs from the WTA questions are generally higher compared to the WTP questions. In the sensitivity analysis, only 126 respondents answered all the six open questions (from the two scenarios) with values above \$0. From these answers, individual quotients (WTA divided by WTP for questions with the same risk reduction) were calculated. The median of these individual quotients was 10.0, with a 95% confidence interval (CI) ranging from 8.0 to 10.0. In related work, Horowitz and McConnell (73) reported that respondents' WTA getting compensated for giving up a good was 5.5 times higher compared to their WTP for the same good. However, both scenarios (WTP to avoid exposure from radon and WTA compensation for exposure from X-ray machines) were judged to be valid in Paper III. Therefore, an overall median VSL of \$50 million was calculated from the sensitivity analysis of all six open questions.

As mentioned above, the timescale of radiation-induced cancer included in the given scenarios in Paper III was 'one or several decades', thus a discounting-factor for the respondents' WTP and WTA was not required. Therefore, the ICRP's detriment-adjusted nominal risk coefficient for workers of 4.2×10^{-2} per Sv was applied in Paper III to convert the given VSL (of \$50 million) into an α value. Furthermore, the excess burden of taxes was also taken into account (in Paper III) for public fund investments in occupational radiological protection within the Swedish healthcare system. The excess burden of taxes concerns the fact that societies are negatively impacted by taxes in the form of a reduced labour supply and the price of goods (156). Therefore, the Swedish Transport Administration (156) recommends a factor of 1.3 to take account of the excess burden of taxes. In this context, the α value should be decreased with same factor (divided by 1.3) for public fund investments. In Paper III, a recommended α value for workers in Sweden, especially useful for the healthcare system, was provided as $1,600 per man·mSv (2024 USD) with an interquartile range (IQR) of $320-$11,700. These figures were recalculated as $2,100 per man·mSv (IQR $420-$15,200) when the excess burden of taxes was excluded.

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4.1.4 COMPARISON OF RECOMMENDED ALPHA VALUES

A comparison of the recommended α values in Papers I, II and III for workers in Sweden is presented in Table 9. These α values were updated into 2025 USD by means of Equation 4. As described above, both Papers I and II are based on the benefit transfer method, where societal costs from other risk contexts are transferred into the specific risk context of interest (occupational radiological protection). Paper II can be seen as an improvement of Paper I. In Paper II, a new method for converting societal costs into an α value was provided (described in Section 4.3). Furthermore, the societal costs of productivity losses and healthcare costs related to radiation-induced cancer were included in Paper II, which was not the case in Paper I. In Section 5 (Discussion), the disparity between Paper II (based on a benefit transfer) and Paper III, based on a survey of the specific risk context of interest, will be further examined, together with other α-value recommendations provided in the literature.

Table 9. A comparison of recommended α values for workers in Sweden, provided in Papers I, II and III.

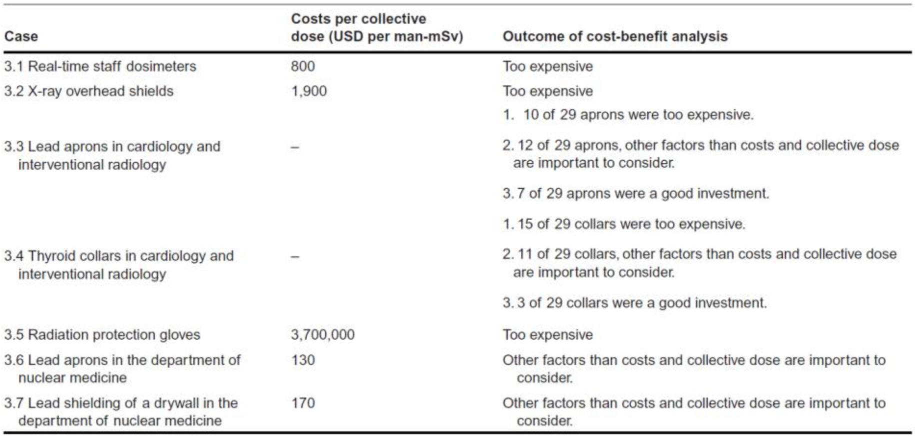
Publications	Provided α values in publications [USD per man·mSv]	Updated α values [USD per man·mSv]
Paper I	45-450 (2021 USD)	55-550 (2025 USD)
Paper II	62-163 (2023 USD)	64-169 (2025 USD)
Paper III	1,600 (2024 USD)	1,600 (2025 USD)

4.2 CASES OF COST-BENEFIT ANALYSIS IN OCCUPATIONAL RADIOLOGICAL PROTECTION WITHIN THE SWEDISH HEALTHCARE SYSTEM

As mentioned in Section 2.4, to the best of the author’s knowledge only a few examples of CBAs in the context of radiological protection within the healthcare system exist in the literature (44–47). From this circumstance, one of the two aims of Paper I (p.297) was: ‘to describe CBAs in occupational radiological protection within the healthcare system of Sweden’. In Paper I, seven cases of CBAs were presented: real-time staff dosimeters, overhead

X-ray shields, lead aprons in cardiology and interventional radiology, thyroid collars in cardiology and interventional radiology, radiation protective gloves, lead aprons in the department of nuclear medicine and lead shielding of a drywall in the department of nuclear medicine. All seven cases originated from clinical practice in Skaraborg Hospital, Sweden. As recommended by the US department of Energy (32) and the IAEA (35), realistic assumptions of variables were applied in these cases (in Paper I) as opposed to so-called worst-case scenarios, where all variables are set to an extreme value to be on the safe side. The costs per collective dose reduction of the seven CBA cases were analysed with the recommended interval for α values provided in Paper I ($45-$450 per saved man·mSv), here these outcomes are reproduced in Table 10. These cases indicate a wide range of costs per collective dose reduction for investments in occupational radiological protection within the Swedish healthcare system. Moreover, several of these cases were considered too expensive. Paper I provides the details of all seven CBA cases, while three of them are briefly described in this thesis.

Table 10. Seven CBA cases in occupational radiological protection within the Swedish healthcare system. This table is reproduced from: 'A case study of cost-benefit analysis in occupational radiological protection within the healthcare system of Sweden' by Engström et al. (Paper I), J Appl Clin Med Phys, 2021;22(10):295-304, licensed under CC BY 4.0 (2).



Case	Costs per collective dose (USD per man-mSv)	Outcome of cost-benefit analysis
3.1 Real-time staff dosimeters	800	Too expensive
3.2 X-ray overhead shields	1,900	Too expensive
3.3 Lead aprons in cardiology and interventional radiology	–	1. 10 of 29 aprons were too expensive. 2. 12 of 29 aprons, other factors than costs and collective dose are important to consider. 3. 7 of 29 aprons were a good investment.
3.4 Thyroid collars in cardiology and interventional radiology	–	1. 15 of 29 collars were too expensive. 2. 11 of 29 collars, other factors than costs and collective dose are important to consider. 3. 3 of 29 collars were a good investment.
3.5 Radiation protection gloves	3,700,000	Too expensive
3.6 Lead aprons in the department of nuclear medicine	130	Other factors than costs and collective dose are important to consider.
3.7 Lead shielding of a drywall in the department of nuclear medicine	170	Other factors than costs and collective dose are important to consider.

4.2.1 REAL-TIME STAFF DOSIMETERS

The use of real-time staff dosimeters has been reported to provide a substantial effective dose reduction for staff exposed to X-rays. Within cerebral angiography, James et al. (157) reported an effective dose reduction of 70% for physicians and 50% for assistant nurses. Within cardiology, Sandblom et al. (158) documented an effective dose reduction of 59% for physicians and

40% for nurses. Moreover, Slegers et al. (159) revealed an effective dose reduction of 46% for pain physicians for a combination of real-time staff dosimeters use and staff coaching in techniques to decrease exposure.

At Skaraborg Hospital, two new systems of real-time staff dosimeters (with a total of 20 dosimeters) were installed in 2012. The cost was $56,000 and the two systems were presumed to be operational for 10 years before disposal. During this period, the collective dose reduction from these systems was assessed to be 70 man·mSv at Skaraborg Hospital. This corresponds to a cost of $800 per saved man·mSv, which, according to the interval of recommended α values in Paper I ($45-$450 per man·mSv), was considered too expensive.

4.2.2 OVERHEAD X-RAY SHIELDS

In 2014, a vendor visited Skaraborg Hospital to present their new overhead X-ray shield model. Compared to the vendor’s old model (already in use in an angiography room at Skaraborg Hospital), the new model was larger and had an overlapping panel curtain at the bottom of the shield. The vendor also presented a published study (160) showing that, at a height of 140 cm above the floor (typically at breast height), the dose reduction achieved by their new model was 68.4 ± 7.4% compared to their old model. The price of this new overhead X-ray shield model was $4,000.

At the time of the vendor’s visit, the staff (cardiologists and nurses) working in the angiography room of interest were being exposed to a collective dose of 0.3 man·mSv per year (measured at breast height). It was assumed that a newly purchased overhead X-ray shield could be used for 10 years before disposal. In a CBA, the cost of this new overhead X-ray shield model was calculated to be $1,900 per saved man·mSv. According to the interval of α values in Paper I, this was considered too expensive.

4.2.3 LEAD APRONS IN CARDIOLOGY AND INTERVENTIONAL RADIOLOGY

In 2019, the purchase price of a new lead apron for Skaraborg Hospital was approximately $590. In the hospital’s cardiology and interventional radiology departments, lead aprons are typically taken out of use and discarded after about 5 years. With a recommended interval for α values of $45-$450 per man·mSv, this means that a lead apron must prevent a collective dose of 2.6 man·mSv per year to be considered a good investment. Lead aprons preventing less than 0.26 man·mSv per year are considered too expensive.

Bearing in mind that the effective dose reduction of wearing a lead apron has been estimated to be about 90% (100), the collective dose reduction obtained from each of the 29 personally used lead aprons within cardiology and interventional radiology departments at Skaraborg Hospital was examined. According to the recommended α values in Paper I, 7 of these 29 personally used lead aprons could be considered a good investment, while 10 could be considered too expensive. The costs of the remainder (12 lead aprons) were analysed to be within the interval of recommended α values. For these lead aprons, it is important to consider factors other than costs and collective dose when assessing the outcomes of these investments. In a way it is quite simple: a lead apron that is not used very much is difficult to classify as a good investment. As stated, these 29 lead aprons were all seen as personal belongings, worn by only one staff member. If lead aprons of various sizes are shared, they are likely to be used more frequently, which increases the justification for such an investment. This conclusion has also been reported by Russel and Hufton (161).

4.3 HOW TO CONVERT SOCIETAL COSTS INTO AN ALPHA VALUE

One of the two aims in Paper II (p.2) was: ‘to develop a new conversion method on how to convert societal costs into an α value’. As described in Section 2.6, this new conversion method was inspired by the work of Mubayi et al. (90) published in 1995. In Paper II, three of the variables used in Mubayi et al.’s work (90) were updated: the risk of exposure, the DR and the NYEC. Of these, the NYEC was subject to most alteration.

4.3.1 RISK OF EXPOSURE

The risk of exposure presented in Paper II was adapted from the ICRP’s nominal risk coefficient R_{lq} adjusted for lethality and quality of life, reported upon in publications 103 (4) and 152 (162). R_{lq} is determined for different cancer sites by Equation 5:

$$R_{lq} = R\big(l + q(1 - l)\big) \qquad \text{Equation 5}$$

where R is the radiation-induced cancer incidence [cases per 10,000 persons per Sv], l is the lethality, and q is the loss of quality of life for different cancer sites (4,162). Thus, R_{lq} takes into account both mortality and morbidity related to different cancer sites and was therefore (in Paper II) deemed to be an appropriate variable for the risk of exposure. The ICRP also differentiates R_{lq} between the general public (0-89 years) and workers (18-64 years) (4,162).

4.3.2 DISCOUNT RATE

The DRs applied in Paper II were derived from a review published by Sharma et al. (163), which encompassed 30 national healthcare economic evaluation guidelines. In this review the recommended DRs were distributed as follows: 3 countries recommended a DR of 1.5%, 1 country 2%, 10 countries 3%, 5 countries 3.5%, 1 country 3.7%, 3 countries 4%, and 7 countries 5%. Thus, the most common DR recommendations were 3% and 5%, a conclusion also reached in other reviews of DRs (91,164–166). Khorasani et al. (166) reported that a frequently used approach to determine a DR is to look at other recommendations for DRs, which they labelled the comparability approach.

4.3.3 NUMBER OF YEARS BETWEEN EXPOSURE AND CANCER DIAGNOSIS

The NYEC is difficult to find in the literature. Related figures, such as the years of life lost from radiation-induced cancer death and the latency period (the minimum time between exposure and cancer diagnosis), are more accessible. Mubayi et al. (90) applied a latency period of 2, 5 or 10 years (depending on the cancer site) when taking into account the discounting-factor for the future risk of radiation-induced cancer. In Paper II, the NYEC was obtained from the ICRP's detriment calculation methodology, which is described in detail in publication 152 (162). In summary, the ICRP's excess risk models follow a linear dose response based on three variables: the absorbed dose d, age at exposure e and attained age a. Furthermore, the ICRP applies fitting parameters β, α_1 and α_2 to account for different sexes (male and female), different populations (Euro-American and Asian), different risk models (excess absolute risk and excess relative risk) and different cancer sites (oesophagus, stomach, colon, liver, lung, ovary, bladder, thyroid and other solid cancers). The excess risk is presented in Equation 6 (162):

$$Excess\ risk = \beta \cdot d \cdot exp\left(\alpha_1 \frac{e-30}{10} + \alpha_2 ln \frac{a}{70}\right) \qquad \text{Equation 6}$$

To calculate the exposure-induced cancer incidence, the ICRP multiplies these excess risk models with general cancer-free survival functions. In this way, the variable of attained age (age when receiving a radiation-induced cancer diagnosis) can be predicted based on the other variables comprising different ages at exposure, absorbed doses, sexes, populations, risk models and cancer sites. Two separate examples are provided: the excess risk of colon cancer [cases per 10,000 persons per 0.1 Gy] for new-born Euro-American girls is presented in Figure 3 based on the excess absolute risk model (reproduced from Paper II) and in Figure 4 based on the excess relative risk model. As can be seen for both risk models (in Figures 3 and 4), the highest excess risk of colon cancer is at an attained age of about 65-80 years, that is, 65-80 years after exposure for new-borns. In the excess absolute risk model (Figure 3), the risk of colon cancer increases with attained age up to about 75 years and thereafter declines due to the impact of the general cancer-free survival function. In the excess relative risk model (Figure 4), the relative risk of colon cancer declines with attained age in relation to the baseline risk of colon cancer. However, in absolute terms the baseline risk of colon cancer increases with attained age. Furthermore, the ICRP presents the baseline risk of colon cancer in 5-year intervals (162). Therefore, the function in Figure 4 appears slightly chopped. In this framework, it should also be noted that the ICRP applies other risk models for some cancer sites (leukaemia, female breasts, skin and bone) compared to those presented here.

In Paper II, attained age was averaged over sexes, populations and excess risk models. Thereafter, Monte Carlo simulations were performed (with Microsoft Excel 365 (167)) to simulate different cancer sites and ages at exposure. As a result, it was possible to iterate a single NYEC value (the difference between attained age and age at exposure) for both the general public and workers. Monte Carlo simulations of 10,000 iterations showed that the NYEC median (IQR) for all cancer sites was 42 (25-58) years for the general public and 34 (21-46) years for workers.

As described in Section 4.1.2, the years of potential working life lost from radiation-induced cancer death were simulated in a comparable way in Paper II. Rather than using NYEC, the simulation modelled the years between a fixed retirement age of 65 and the attained age. Cancers that were simulated to occur after the age of 65 were set to 0 years of potential working life lost. These Monte Carlo simulations showed that a mean of 7.6 years of working life is lost due to radiation-induced cancer deaths for the general public, whereas the corresponding mean for workers is 5.4 years. These figures actually relate to the number of years between retirement and cancer diagnosis. However, due to the lack of better estimations, these figures were applied as the number of years between retirement and cancer death, which is stated as a limitation in Paper II.

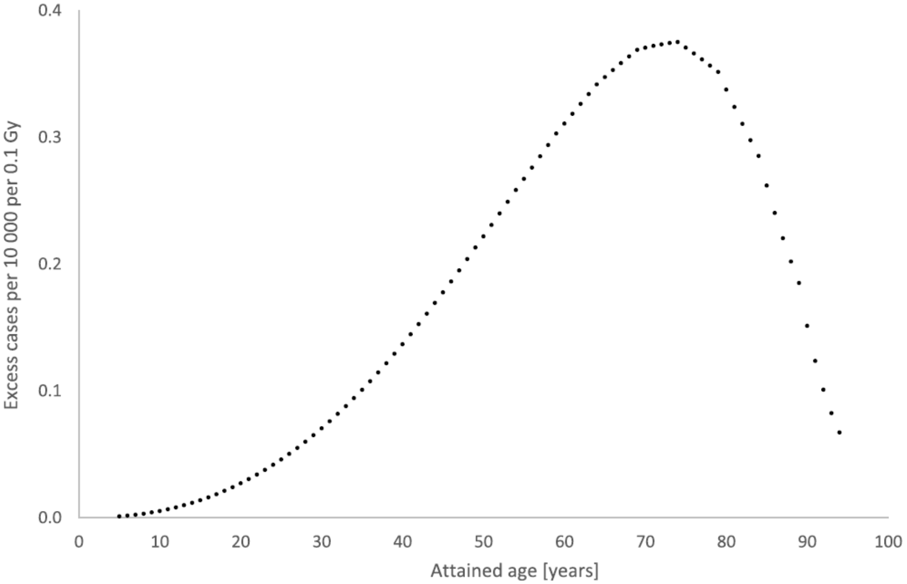


Figure 3. The excess risk of colon cancer [cases per 10,000 persons per 0.1 Gy] based on the excess absolute risk model for new-born Euro-American girls, depending on attained age. This figure is reproduced from: 'How much resources are reasonable to spend on radiological protection?' by Engström et al. (Paper II), J Radiol Prot, 2024;44(4):041516, licensed under CC BY 4.0 (2).

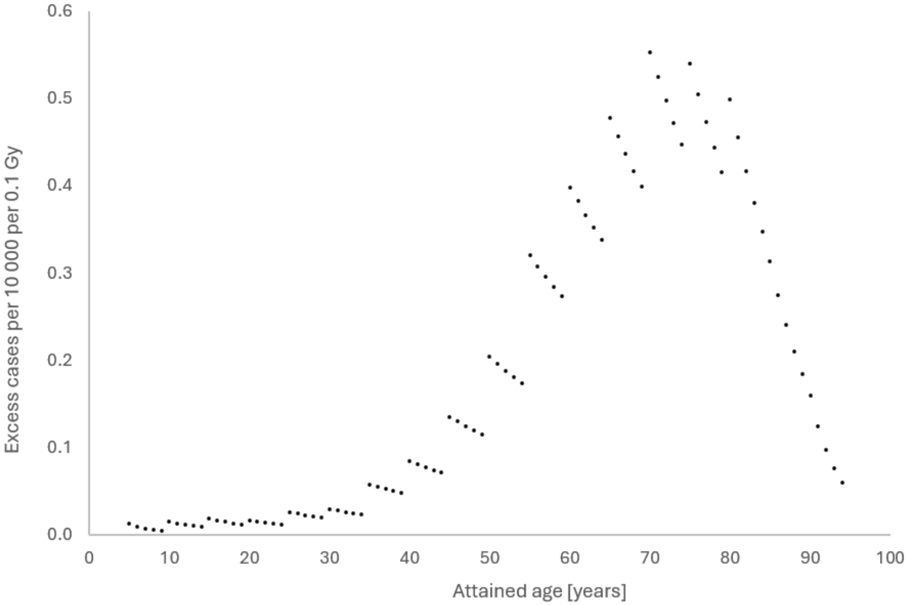


Figure 4. The excess risk of colon cancer [cases per 10,000 persons per 0.1 Gy] based on the excess relative risk model for new-born Euro-American girls, depending on attained age.

4.3.4 DISCOUNTED RISK OF EXPOSURE

Monte Carlo simulations of the discounted nominal risk of exposure R_{lq} were conducted (in Paper II) using the DR and $NYEC$ distributions as explained above and by Equation 7 (which is similar to Equation 3):

$$Discounted\ R_{lq} = \frac{R_{lq}}{(1 + DR)^{NYEC}} \qquad \text{Equation 7}$$

Using Microsoft Excel 365 (167), 10,000 iterations of the discounted R_{lq} were simulated for both the general public and workers in Paper II. The result for the general public is shown in Figure 5 as a histogram. In these simulations, the discounted nominal risks of exposure R_{lq} had a median (IQR) of:

- 175 (136-222) per 10,000 persons per Sv for the general public
- 169 (134-207) per 10,000 persons per Sv for workers.

By considering discounting (in this context considering that people prefer to postpone a future risk compared to facing it today), the discounted R_{lq} for the general public is about 70% lower compared to the undiscounted R_{lq}, reported by the ICRP (4) to be 565 per 10,000 persons per Sv. The discounted R_{lq} is also about 70% lower compared to the ICRP's detriment-adjusted nominal risk coefficient for the general public of 574 per 10,000 persons per Sv (4). The latter coefficient is frequently applied as a conversion coefficient between societal costs and an α value (44,51,54,74,85,86), as described in Section 2.6. For workers, the simulation of a median discounted R_{lq} is about 60% lower compared to the corresponding figures of the ICRP's undiscounted R_{lq} and detriment-adjusted nominal risk coefficients (4).

These median discounted R_{lq}-values are useful when converting societal costs into an α value for the general public and for workers. However, in Paper II the uncertainties pertaining to societal costs (general VSL, productivity losses and healthcare costs) were considered. Therefore, societal costs were incorporated into the Monte Carlo simulations, together with the discounted R_{lq}, to provide useful α-value recommendations. With regard to the recommended α values in Table 7, the intervals for the general public are wider compared to those for workers. These results can be derived from the wider IQRs of the recommended discounted R_{lq} for the general public compared to workers, and even further back from the wider IQR of NYEC for the general public compared to workers.

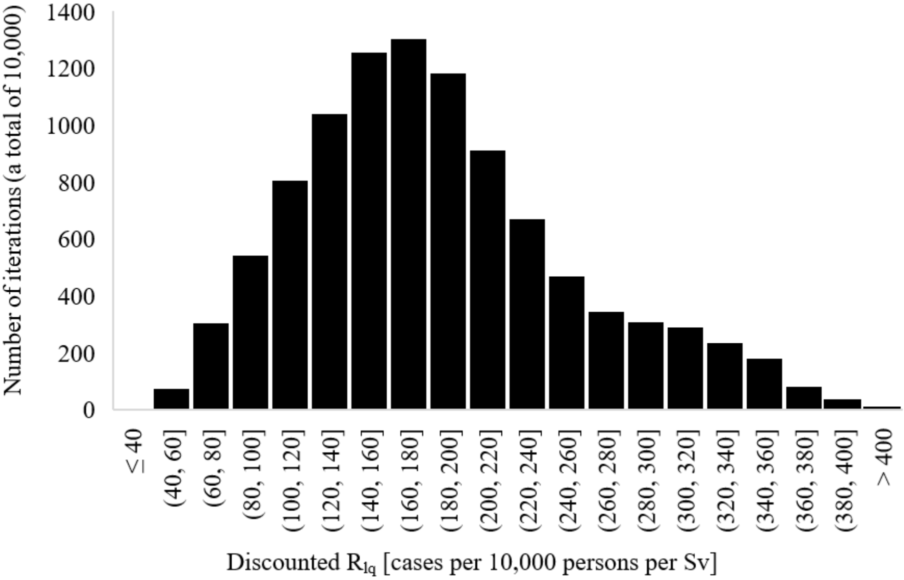


Figure 5. Histogram of Monte Carlo simulations (10,000 iterations) of the discounted nominal risk of exposure R_{lq} [cases per 10,000 persons per Sv] for the general public.

4.4 STAKEHOLDER INVOLVEMENT REGARDING LEAD APRONS AND THYROID COLLARS

To promote stakeholder involvement, the aim of Paper IV (p.2) was: ‘to investigate staff’s experience of discomfort associated with wearing lead aprons and thyroid collars for long periods of time, and also to investigate staff’s willingness to tolerate personal dose equivalent (expressed as radiation dose) and the corresponding increase in future cancer risk to avoid wearing these protective tools’. In Paper IV, a survey was distributed to 255 staff members at Skaraborg Hospital (physicians, radiographers, nurses and assistant nurses) immediately before their radiation safety education (which is repeated every three years). The survey was given specifically to staff who regularly use lead aprons and thyroid collars for long periods of time while working in cardiology, interventional radiology, and other operating theatres. Answers were received from 245 out of the 255 staff members, a response rate of 96%.

In Paper IV, the respondents were asked about discomforts (bothersome warmth, fatigue, ache or pain) linked to wearing lead aprons and thyroid collars. One of the questions was: ‘Have you ever had, or do you currently have, any pain or discomfort in the neck, shoulders, or back? [yes/no]’ (author’s translation), followed by: ‘Do you feel that this pain or discomfort originates from, or is aggravated by, wearing a lead apron at work? [yes/no]’ (author’s translation). Respondents who answered ‘yes’ to both these questions were understood as experiencing discomforts that they themselves thought were linked to wearing lead aprons. Of the respondents:

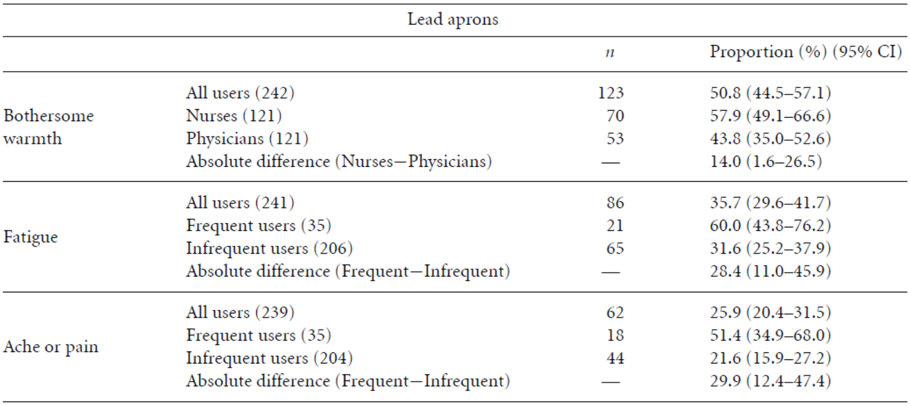
- 50.8% (95% CI 44.5%-57.1%) experienced bothersome warmth
- 35.7% (95% CI 29.6%-41.7%) experienced fatigue
- 25.9% (95% CI 20.4%-31.5%) experienced ache or pain

that they themselves believed were linked to wearing lead aprons for long periods of time. These results, together with significant absolute differences between subgroups of respondents (different occupations and differences in frequency of wearing lead aprons), are presented in Table 11. Significant differences were not found between subgroups by sex or by age. Discomforts linked to wearing thyroid collars were less common compared to lead aprons. For thyroid collars:

- 31.3% (95% CI 25.2–37.3%) experienced bothersome warmth
- 13.2% (95% CI 8.8–17.5%) experienced fatigue
- 6.7% (95% CI 3.4–9.9%) experienced ache or pain

that the respondents themselves believed were linked to wearing thyroid collars for long periods of time.

Table 11. The respondents reported discomfort (bothersome warmth, fatigue, ache or pain) linked to wearing lead aprons for long periods of time. Significant absolute differences are reported between subgroups of respondents where they could be found. This table is reproduced from: ‘Lead aprons and thyroid collars: to be, or not to be?’ by Engström et al. (Paper IV), J Radiol Prot, 2023;43(3):031516, licensed under CC BY 4.0 (2).



Lead aprons			
		n	Proportion (%) (95% CI)
Bothersome warmth	All users (242)	123	50.8 (44.5–57.1)
	Nurses (121)	70	57.9 (49.1–66.6)
	Physicians (121)	53	43.8 (35.0–52.6)
	Absolute difference (Nurses−Physicians)	—	14.0 (1.6–26.5)
Fatigue	All users (241)	86	35.7 (29.6–41.7)
	Frequent users (35)	21	60.0 (43.8–76.2)
	Infrequent users (206)	65	31.6 (25.2–37.9)
	Absolute difference (Frequent−Infrequent)	—	28.4 (11.0–45.9)
Ache or pain	All users (239)	62	25.9 (20.4–31.5)
	Frequent users (35)	18	51.4 (34.9–68.0)
	Infrequent users (204)	44	21.6 (15.9–27.2)
	Absolute difference (Frequent−Infrequent)	—	29.9 (12.4–47.4)

If only considering the first question presented above: ‘Have you ever had, or do you currently have, any pain or discomfort in the neck, shoulders, or back? [yes/no]’, then 80.0% (95% CI 66.7–93.3%) of frequent users of lead aprons (>10 h/w) reported experiencing ache or pain in their neck, shoulders or back. For infrequent lead aprons users (⩽10 h/w), only 59.3% (95% CI 52.6–66.1%) reported ache or pain in these areas. The absolute difference between frequent and infrequent users of lead apron was calculated as 20.7 percentage points (95% CI 5.8–35.6 percentage points). This result (from Paper IV) will be compared with other studies within this field in Section 5.7 to investigate the possible link between ache or pain and the use of lead aprons for long periods of time.

In Paper IV, the respondents were asked to state a radiation dose (personal dose equivalent) per year that they would tolerate to avoid wearing lead aprons and thyroid collars for long periods of time. In the same context, they were also asked how great an increase in their future cancer risk they were willing to tolerate in order to avoid wearing these protective tools. To help the respondents answer these questions, they were given information about the natural background radiation level and general baseline future cancer risks. One of these questions was framed as: ‘The risk of 25-year-olds receiving a cancer diagnosis at some point during the rest of their lives is estimated at 43%. How great an increase in future cancer risk would you tolerate in exchange for not having to use lead aprons during your working life?’ (author’s translation). The alternatives presented were: from 43% to 60%, from 43% to 50%, from

43% to 47%, from 43% to 45%, from 43% to 44%, from 43% to 43.2%, from 43% to 43.02%, from 43% to 43.002%, no increased risk at all, or I do not want to take a position on this question.

In order to compare the respondents' answers about personal dose equivalent per year with their answers about an increased future cancer risk, Monte Carlo simulations in the RadRAT program (168) were used together with an organ dose estimation method provided by Simon et al. (96). Figure 6 presents the results (as cumulative ratios) of the respondents' willingness to tolerate a personal dose equivalent per year as well as their reported willingness to tolerate the matching increase in future cancer risk to avoid wearing lead aprons. About one-third of the respondents answered that they would tolerate a personal dose equivalent of 1 mSv per year or more to avoid wearing lead aprons. However, only one fifth of the respondents answered that they would tolerate the matching increase in their future cancer risk from 43% to 43.2%. By merging nurses, assistant nurses and radiographers into a single group called nurses, the respondents could be divided into four categories (male-physicians, female-physicians, male-nurses and female-nurses). A significant difference ($p = 0.003$) could be found between male-physicians and male-nurses, where male-physicians tolerated a higher personal dose equivalent per year compared to male-nurses. Significant differences could also be found between female-physicians and female-nurses, where female-physicians tolerated a higher personal dose equivalent per year compared to female-nurses ($p = 0.007$), and also that female-physicians tolerated a higher increase in their future cancer risk compared to female-nurses ($p < 0.001$) to avoid wearing lead aprons. In Paper IV, no significant differences could be found between other subgroups of respondents, that is, the two sexes, age groups or frequency of using lead aprons. Overall, the respondents tolerated a higher personal dose equivalent per year compared to the matching increase in future cancer risk ($p < 0.001$). It should also be noted that 74% of all respondents did not tolerate an increase in their future cancer risk from 43% to 43.002% to avoid wearing lead aprons, the smallest risk-increase in the close-ended question.

In the last question in Paper IV, the respondents were asked about their opinion on rules regarding lead aprons and thyroid collars. Of the respondents, 72% stated that the Swedish Radiation Safety Authority should decide these rules, 23% indicated that the decision should rest with the employees themselves, and 5% answered that they did not want to take a position on this topic. This result will be discussed further in Section 5.7.

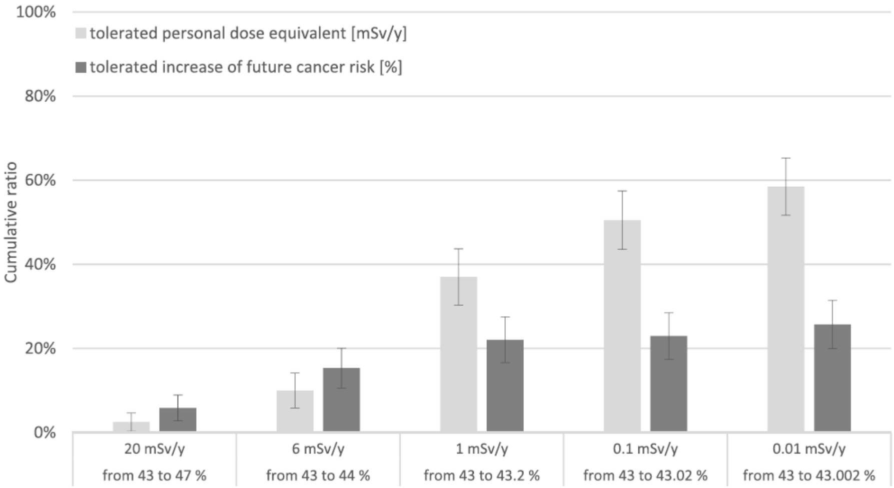
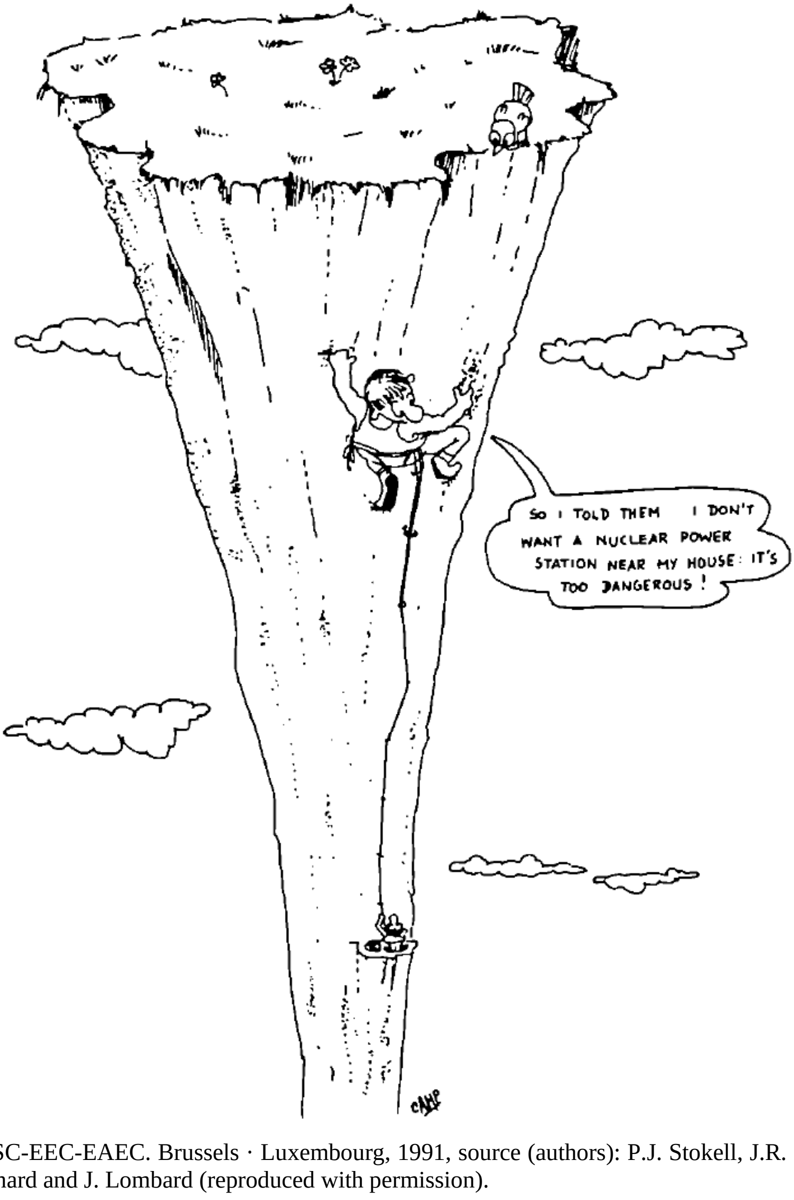


Figure 6. Presented as cumulative ratios, the respondents' reported willingness to tolerate personal dose equivalent per year and their reported willingness to tolerate the matching increase in their future cancer risk to avoid wearing lead aprons. The 95% CI of the proportions are indicated by the error bars. This figure is reproduced from: 'Lead aprons and thyroid collars: to be, or not to be?' by Engström et al. (Paper IV), J Radiol Prot, 2023;43(3):031516, licensed under CC BY 4.0 (2).



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5 DISCUSSION

The discussion starts with the linear no-threshold (LNT) model, upon which the ALARA principle is based. Thereafter, the discussion continues with a presentation of cultural theory and how it can describe people’s attitudes towards risks and CBAs. Furthermore, detailed discussions on CBA, VSL and α values will be presented. Additionally, a final α-value recommendation will be proposed and discussed. Also, a discussion about people’s interpretations of risks and how such interpretations affect the use of lead aprons will be provided. Finally, an ethical discussion on the four papers will be given.

5.1 THE LINEAR NO-THRESHOLD MODEL

The work in this thesis about CBAs and α values is based on the ALARA principle, which in turn originates from the LNT model for radiation effects. The ICRP adheres to the LNT model and defines it as follows (4 p.26): ‘A dose-response model which is based on the assumption that, in the low dose range, radiation doses greater than zero will increase the risk of excess cancer and/or heritable disease in a simple proportionate manner’. The correctness and the usefulness of the LNT model has been extensively debated ever since it was introduced (169), and it can be traced back as far as to 1928 (170). Wilson et al. (169) conducted a literature review of low dose research published between 2013 and 2023. They found 40 papers (on cell structures, animals and epidemiological studies on humans) without a clear consensus about the LNT model. Their conclusion was simply (169 p.394): ‘it is complicated’. However, they also stressed (169 p.394): ‘Without a clear scientific consensus of the risk in humans, there is little case to move away from LNT as a regulatory approach’. Voices critical of the LNT model (171–173) argue that in epidemiological studies the LNT model is often considered the null hypothesis. No epidemiological studies on humans can provide evidence for discarding the LNT model because of the limited statistical power at low doses (<100 mSv) (171). However, failing to reject the null hypothesis is not the same as recognising its validity (173,174). A statistically correct null hypothesis would be that of no association between low doses and radiation effects (171). The burden of proof for the validity of the LNT model begins with the claim of the null hypothesis (173). There is a difference between reviewing epidemiological studies in search of support for the LNT model and seeking evidence to reject it (171). Moreover, promoters of the LNT model have been criticized for cherry-picking data (171), for grouping data into wide dose intervals, which can hide evidence of a non-linearity causation (172), for ignoring methodological problems in epidemiological studies (171), for not including background radiation of the 'unexposed' control group (172) and for ignoring the fact that DNA repair mechanisms after exposure are not considered to be linear (173). The LNT model and its extension, the ALARA principle, have also been condemned for spreading radiophobia (169,172,173,175), for providing extreme estimates of clean-up costs in the aftermath of nuclear fallouts (169,172,173) and for leading to suboptimal image quality in medicine including the risk of missed diagnoses (1). The ICRP acknowledges parts of this criticism, but nevertheless considers the LNT model together with a dose and dose rate effectiveness factor (that adjusts the life time risks of radiation effects downward by a factor of 2) to be a 'prudent basis for the practical purposes of radiological protection' (4). This might remind us of a famous quotation from the British statistician George Box (169 p.386, 176): 'All models are wrong, but some are useful'. Furthermore, the uncertainties of the LNT model are closely linked to the core ethical value of prudence, described in the Introduction (Section 2) as the ability of 'making informed and carefully considered choices without full knowledge of the scope and consequences of an action' (9 p.11).

5.2 CULTURAL THEORY

In sociology, people's attitudes toward the use of CBA have been analysed through the lens of cultural theory (177). Originally introduced by Douglas in 1970 (178), cultural theory explains how shared values and patterns of interpersonal relationships combine to form distinct 'ways of life' (177,179). The different ways of life are divided into two dimensions. The group dimension describes how strongly individuals feel connected to bounded units. For example, an individual who feels a strong connection to others in their residential area, workplace, and recreational settings is likely to experience a strong sense of group affiliation. The stronger that connection is, the more individual decisions tend to be influenced or even determined by the group. The grid dimension describes how strongly individuals feel circumscribed by externally imposed rules and expectations (social control). The more institutionalised they feel, the lesser their experience of having control over their individual choices. By crossing these two dimensions (like crossing two axes), cultural theory describes the four different ways of life as: hierarchists, egalitarians, individualists and fatalists, see Figure 7 (177,179,180).

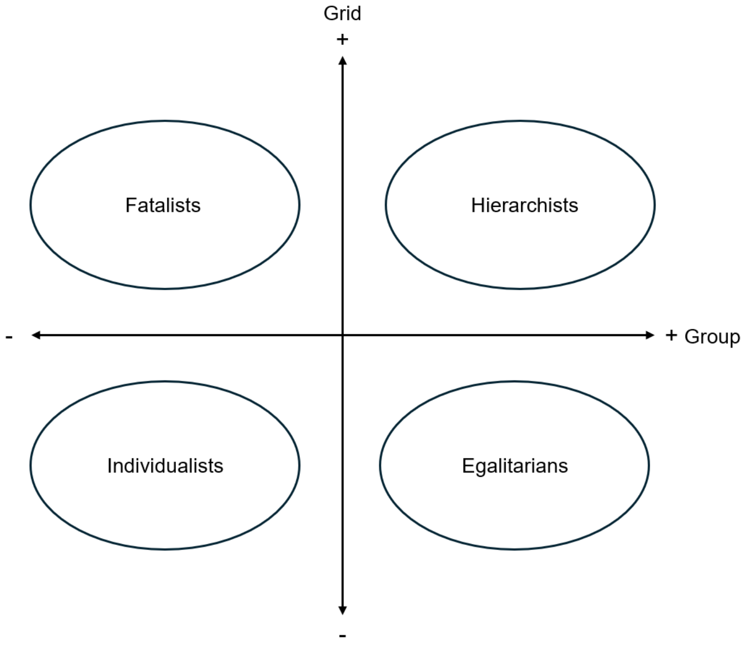

Figure 7. Cultural theory describes four different ways of life along the group and grid dimensions as: hierarchists, egalitarians, individualists and fatalists.

Hierarchists feel both a strong group and a strong grid dimension. In a hierarchical world, social relationships require that everyone knows their place. Hierarchists justify the power of authorities by their conviction that when people are assigned different roles, it helps them to live together in harmony. Examples of communities with a high degree of hierarchy are military forces and the Hindu cast system (177,179). Egalitarians also feel a strong group dimension, but unlike hierarchists, they feel a weak grid dimension. In an egalitarian world, equity and democracy are the most important aspects of life. Control over others can only be claimed by speaking on behalf of the group. An environmental protest organisation can serve as an example of an egalitarian world (177,179). Moreover, individualists feel both a weak group and a weak grid dimension. In an individualistic world, regulation by authorities should be minimal and a free market is the desirable solution to most problems. Individualists often measure their success in wealth. Examples of an individualistic lifestyle are a self-made entrepreneur or a risk-taking investment banker (177,179). Finally, fatalists feel a weak group dimension but a strong grid dimension. In a fatalistic world, people have little control over their lives and feel powerless to change their destiny. Fatalists are coping, and even when good things occur to them, they do not see the connection to their own efforts. An example of a fatalist might be the low-paid, non-unionised employee (177,179).

Over time people sometimes transform in their way of life (179). For example, when a person’s financial situation drastically changes, such as when the rich, self-made individualist suddenly goes bankrupt, that person can turn into a fatalist, blaming society for their failure. The opposite is also true, as fatalists sometimes get an opportunity to haul themselves up the economic ladder and therefore start to see themselves as individualists. Transformations between other ways of life are also possible (179). Moreover, in the above extreme descriptions of the four different ways of life, it is not unusual to recognise parts of oneself in several of them. People might even fall into different ways of life between work and leisure time. The phenomenon when humans adapt to their social context has been termed ‘the multiple self’ (179).

Interestingly, these four ways of life tend to feel differently when it comes to decision-making about risks (177,179–181). Hierarchists believe that decisions about acceptable risks should be made by authorities governed by experts. They see CBA as a rational management tool that serves societies well. When disputes about the proof of danger occur, they look for answers in more research (177,179–181). On the other hand, individualists see risk as an opportunity and believe that it should be up to the individual to decide about acceptable risk levels. Individualists are pragmatic and see CBA as a useful tool when it produces the ‘correct’ answer. Individualists are strongly in favour of development and believe that the burden of proof rests on those who see something new as harmful (177,179–181). According to egalitarians, decisions about acceptable risk levels should be based on openness, trust and above all, consensus. Trying to measure the value of a statistical life may be perceived as unethical, and egalitarians are often sceptical of the use of CBA. It is better to be safe than sorry, and the burden of proof rests on those who see something new as harmless (177,179–181). Fatalists feel neglected by a society that is ruled by hierarchists, individualists and egalitarians. Therefore, they do not really worry about risks and CBAs that they cannot control, which sometimes endows them with an admirable stoic dignity (177,179–181). To summarise, arguments about what can be considered an acceptable risk level or the usability of CBAs cannot be easily resolved, as these arguments stem from fundamental differences between the four ways of life (177).

5.3 REFLECTION ON COST-BENEFIT ANALYSIS

In the short term, a society’s resources (including financial, human, and natural) are finite and must be prioritised (3,33). For example, there are 128,000 accidental deaths per year in the U.S. (182). If (unrealistically) the entire U.S. gross domestic product per year were to be devoted to preventing these deaths, there would be a finite number of $115 million allocated per avoided accidental death (182). In this context, the term ‘opportunity costs’ is frequently applied in health economics. It means that when a society’s financial resources are being used, they should be compared to other needs (other opportunities) within that society. Preferably, a society’s financial resources should be invested where they can return the greatest benefit (183). The Swedish healthcare system is obliged to apply the so-called cost-effectiveness principle. This implies that (184 p.18): ‘when choosing between different activities or interventions, a reasonable relationship between cost and effect, measured in improved health and enhanced quality of life, should be sought’ (author’s translation). In general terms, the need to prioritise resources and to apply CBA is growing in both Europe and the U.S. (43,64,65,185).

As mentioned in the Prologue (Section 1), the ICRP introduced CBA in radiological protection in 1973 (7). Since then, the ICRP has shifted toward a more egalitarian approach, placing greater emphasis on individual equity and justice (186). First, the ICRP introduced different levels of α values depending on individual doses (as described in greater detail in Section 2.2.2 and Section 5.5). Second, the concept of dose constraints was also introduced, yielding a source-related basic level of protection for individuals at the highest risk (4,186). In 2006, the ICRP stated that quantitative DATs (such as CBA) remain valid, but the optimisation process should be viewed more broadly to incorporate individual equity, safety culture and stakeholder involvement (10).

There are several arguments against the application of CBA within radiological protection. Demeter (187) points out that because of the uncertainties associated with the LNT model, the ICRP (4) advises against calculations of the hypothetical number of radiation-induced cancer deaths related to small radiation doses, to which a large number of people are exposed over an extended period of time. Therefore, Demeter (187) argues that it is illogical for the ICRP to also recommend the use of CBAs in radiological protection, as the approach is based on the hypothetical number of radiation-induced cancer deaths. Demeter (187) also stresses that a CBA is seen as a complex task by most radiological protection professionals and that many countries are now attempting to reduce their overall regulatory burden. Furthermore, Reed (188) states that the LNT model probably overestimates the risk of exposure from low doses. Therefore, Reed (188) argues that the use of CBA should be discontinued, suggesting that the ICRP dose limits (for the general public and workers) should be interpreted as acceptable risk levels, with no need to further reduce exposure below these dose limits.

Finally, several problems associated with the implementation of CBAs have been recognised by the ICRP (10). The main obstacles were identified as recognizing relevant factors, collecting adequate data, managing numerous uncertainties, and making the various value judgments required throughout the process. Therefore, the ICRP highlights transparency as an important part of the informed decision-making process (10). Furthermore, several sources (5,10,33,35,40) have reported that while a CBA is a helpful tool for decision-makers, its outcome should not be interpreted as the only correct decision.

5.4 PERSPECTIVES ON THE VALUE OF A STATISTICAL LIFE

As described in Section 2.5, when interpreting the VSL there is often confusion between placing a value on human beings' lives and placing a value on a small decrease in their mortality risk. Consequently, VSL can sometimes be seen as a controversial term (189). Concerns have been raised regarding people's difficulties in estimating the value of a statistical life, as well as their tendency to oppose being asked about it (182). In health economics, the term VSL is well established, and criticism often comes from outside the field. It is also frequently applied in CBAs of government policies in the U.S. and other countries (182).

Davis (190) has questioned whether life is of infinite value. First, she points out that many philosophers and religious leaders describe life as invaluable. Moreover, valuing lives in the same way as houses or cars is seen as unethical by most people in the western world (190). Additionally, if a value is placed on lives, a society's resources might be withheld from those lives that are no longer considered productive, a further appalling thought for most of us. On the other side of the coin, Davis (190) claims that most people sense that in a rescue operation children should be saved first, because it is a greater tragedy when children die (with potentially 70 to 80 years of life remaining) compared to older individuals. In this context, she argues that a week of a life is worth less than a decade of the same life. Furthermore, when lives are valued against each other, most people also take the quality of life into consideration. Davis states (190) that so far, no society has been able to provide their best possible healthcare to all of its citizens at all times; thus, prioritisation of lives has always been necessary. Finally, Davis (190 p.246) closes her discussion with the following statement: ‘It is possible to say at one and the same time that life is both invaluable and capable of being valued’.

Accepting VSL as the value of a small change in the risk or probability of losing a statistical life, Aldy and Viscusi (191) reported an inverted U-shape, with the peak VSL occurring around the age of 40 based on survey results. On the other hand, Carlsson et al. (192) revealed that VSL estimates of children are higher compared to those of adults. However, the U.S. Environmental Protection Agency suggested a senior discount on their VSL estimate in 2002. This suggestion was followed by a political firestorm and therefore rejected (191). In this thesis, no VSL estimates dependent on age were applied, which aligns with the recommendation of the Swedish Transport Administration (96).

As described in Section 2.5 (and further discussed in Section 5.5), VSL estimates are usually characterised as context-dependent (49,51,65,76–79). Regarding VSL estimates based on cancer risks, people may experience a utility loss not only from the possibility of the disease itself but also from the ongoing fear and anxiety that it could affect them in the future. This psychological burden creates costs in the present, which works against the conventional discounting of future costs (182). Several studies have compared respondents’ WTP to avoid a small risk of death from cancer with their WTP to avoid an equivalent risk of death from an accident. Magat et al. (81) reported that their respondents were indifferent in their WTP to avoid a small risk of terminal lymphoma compared to a fatal traffic accident. Moreover, Hammitt and Haninger (82) found no significant difference between their respondents’ WTP to avoid a small risk of fatal cancer versus a fatal automobile accident. In contrast, Hammit and Liu (78) reported that, when outcomes were not limited to mortality, respondents’ WTP to avoid a small risk of cancer was about one-third higher than their WTP to avoid a comparable chronic degenerative disease. Furthermore, Viscusi et al. (77) found a 21% VSL cancer premium compared to acute fatalities in their survey. Guignet and Alberini (79) reported that Italians’ WTP to avoid cancer risks was higher compared to their WTP to avoid cardiovascular and respiratory risks. Interestingly, Guignet and Alberini (79) also reported that British people’s WTP to avoid these various risks was about the same. In 2003, HM Treasury (193) adopted an approach that VSL estimates for cancer deaths should be valued at twice the amount of those for acute accidents. In 2022, HM Treasury abandoned this approach (6). In this thesis, no adjustments regarding cancer risk were made in Papers I and II, where VSL estimates from other risk contexts (environmental, health and transport) were converted into α values for radiological protection. The recommended α value in Paper III, based on a survey of occupational radiological protection, is considerably higher than those recommended in Papers I and II (see Table 9). This circumstance might be a result of people's greater fear of exposure to ionising radiation (and associated cancer risks) compared to other risks such as traffic accidents (194,195).

5.5 ALPHA-VALUE RECOMMENDATIONS IN COMPARISON

As described in Section 2.2.2, an extended form of CBA can take individual doses into account by means of a β value. This approach has also been described in several reports as different α-value levels based on individual doses (3,10,35,196,197). Furthermore, the approach rests on the assumption of equity of exposure, where options with 'high' annual individual dose levels are discarded compared to other options with the same collective dose level but a more homogeneous distribution of the exposure (10). In Equation 8, the recommended aversion coefficient a is between 1.2 and 1.9 (196,198):

$$\alpha = \alpha_{base}\left(\frac{d}{d_0}\right)^a \qquad \text{Equation 8}$$

where α_{base} is seen as the basic α value, d the annual individual dose level for the exposed group and d_0 the lowest dose level at which annual individual doses should be considered (a is set to zero when $d < d_0$). The d_0 value is linked to the acceptance of inequity of exposure and has been recommended to be 1 mSv per year for workers (10,35,196), the same as the effective dose limit for the general public. A graphic presentation of an α value depending on annual individual dose levels has been included in several studies (10,35,196) and is here provided in Figure 8. Valuing equity of exposure can be seen as a reflection of an egalitarian way of life. However, in a hierarchical way of life, it would be pointed out that the theoretical number of radiation-induced cancer cases would be the same between two options with identical collective dose levels, regardless of the homogeneity of the exposure. Therefore, rejecting the option with the highest annual individual dose level for that explicit reason would probably be seen as an illogical act in a hierarchical way of life. In this context, it should be reminded that the application of α values in planned exposure situations is limited to doses below the ICRP dose limits.

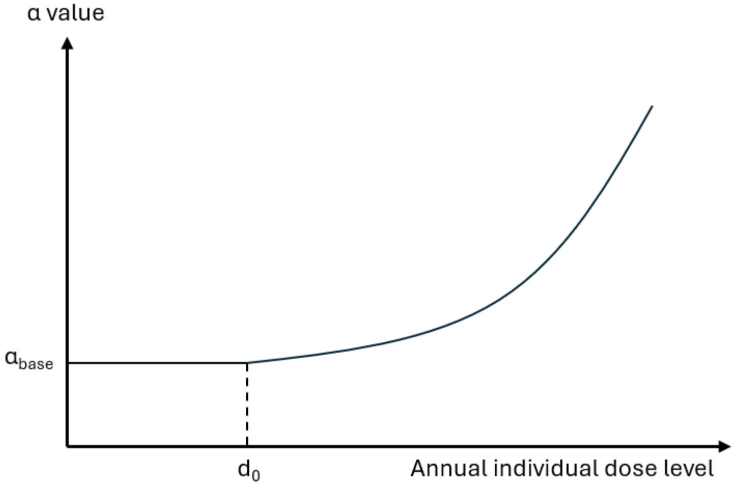

Figure 8. The α value depends on the annual individual dose level (referring to Equation 8).

Throughout this thesis, all recommended α values should be understood as α_{base} values, although for simplicity they are referred to as α values. Paper III included a comparison of α values reported in the literature. In this thesis, Table 12 provides an extended comparison, by incorporating additional references and converting all values to 2025 USD. Adjustments for both the time period and the economic status of the country were carried out using the VSL adjustment method published by the OECD (64), as previously described in Equation 4. With minor modifications of Equation 4, adjusted α values α_{adj} were calculated by means of Equation 9 and historical exchange rates (199):

$$\alpha_{adj} = \alpha_{pub} \cdot \left(\frac{CPI_{present}}{CPI_{past}}\right) \cdot \left(\frac{GDP_{OECD-past}}{GDP_{country-past}} \cdot \frac{GDP_{OECD-present}}{GDP_{OECD-past}}\right)^{0.8} \quad \text{Equation 9}$$

where α_{pub} is the published α value for a specific country, *CPI* the consumer price index (200,201) and *GDP* the gross domestic product per capita (202). An income elasticity of 0.8 was used in the same way as in Equation 4 to take account of the fact that people's WTP to avoid a small risk of death is not strictly proportional to their income (64). By the means of Equation 9, published α values for specific countries were converted into mean α values for the OECD member states (2025 USD), making it possible to compare these α values with each other. The method in Equation 9 also provides the opportunity to update α values in the future and to convert them into recommendations for specific countries. Assuming that citizens of non-OECD member states provide similar responses in surveys of the stated preference approach of VSL (proportional to their income), Equation 9 can also be used to convert α values into recommendations for these countries.

The α-value recommendations in Table 12 are subdivided into the categories on which they are based: the human capital approach, the revealed preference approach, the stated preference approach of a general VSL, the stated preference approach of a VSL within radiological protection and international surveys of α values used by nuclear utilities. Those based on the human capital approach differ by a factor of 14 between the highest and lowest values, with Pandey and Nathwani (55) considered an outlier. These differences originate from partly different methods and assumptions. Regarding VSL estimates, the stated preference approach usually yields higher projected values than the human capital approach (50,203). This is also reflected in Table 12 when comparing α values based on the stated preference approach of a general VSL with those α values based on the human capital approach. For the studies in Table 12 with recommended α values based on the stated preference approach of a general VSL (including Papers I and II), the difference between the highest and lowest values is a factor of 5 (if the recommended α-value intervals are compared as a mean of their interval). Furthermore, in studies with a recommended α value based on the stated preference approach of a VSL within radiological protection (including Paper III), the difference between the highest and the lowest value is a factor of 56. Of these, the recommended α value in Paper III is based on both the WTA and the WTP scenarios, unlike the other α-value recommendations that are only based on the WTP scenario. As described in both Section 2.5 and Section 4.1.3, a WTA scenario often produces a higher VSL compared to a WTP scenario (73). Apart from this factor, the disparity between studies of α-value recommendations based on the stated preference approach of a VSL within radiological protection is difficult to explain. The final category in Table 12 consists of international surveys of α values used by nuclear utilities, published by the Information System on Occupational Exposure, European Technical Centre (ISOE ETC) (41,204–206). These surveys indicates that nuclear utilities have increased their spending on radiological protection over the years, with adjustments made for the time span between surveys (1998 to 2018).

Table 12. For comparison, examples of recommended α values (subdivided into categories), adjusted for the time period and economic status of country.

Publication	Year	Country	α_{base} values, adjusted for time period and country [2025 USD per man·mSv]
The human capital approach			
IAEA (52)	1985	OECD	15
Hardeman et al. (53)	1998[a]	Belgium	82
Eeckhoudt et al. (54)	1999	France	63
Pandey and Nathwani (55)	2003	Canada	920
Na and Kim (56)	2009[a]	South Korea	43
Gordon et al. (57)	2011[a]	Ghana	6
Lee et al. (58)	2012	South Korea	78
Fadul and Na (59)	2016[a]	South Korea	48
Perez et al. (60)	2017[a]	Brazil	38
Linsheng et al. (61)	2019[a]	China	27
The revealed preference approach			
Linsheng et al. (61)	2019[a]	China	340
The stated preference approach of a general VSL			
Bergman (44)	1992	Sweden	300
Bengtsson and Moberg (45)	1993	Sweden	120-620
Baum et al. (51)	1994	U.S.	250
Engström et al. (Paper I)	2021	Sweden	49-490
U.S. NRC (74)	2022[a]	U.S.	310-940
Kotre (46)	2022	U.K.	120
Andresz et al. (75)	2022[a]	France	140
Engström et al. (Paper II)	2024[a]	OECD	65-170
The stated preference approach of a VSL within radiological protection			
Eeckhoudt et al. (54)	1999	France	86
Choi et al. (84)	2001	South Korea	820
Eged et al. (85)	2001[a]	Hungary	25
Katona et al. (86)	2003[a]	Hungary	33
Engström et al. (Paper III)	2024	Sweden	1,400
International surveys of α values, used by nuclear utilities			
ISOE ETC (204)	1998[a]	OECD	200-540
ISOE ETC (205)	2003[a]	OECD	490-5,500
ISOE ETC (206)	2012[a]	OECD	200-7,200
ISOE ETC (41)	2018[a]	OECD	890-10,000

[a] α values were assigned to a few years preceding the year of publication, which is expressed in Table 12.

In the context of cultural theory and radiological protection, the use of an α value based on the human capital approach can be seen as a strictly hierarchical way of life, only compensating for a society's economic loss due to radiation-induced cancer deaths. In this thesis, the recommended α values presented in Papers I, II and III are all based on the stated preference approach, which can be seen as a mixture of hierarchical and egalitarian ways of life. The stated preference approach is also linked to the concept of stakeholder involvement, which is one of the qualitative approaches recommended by the ICRP (10). To be more precise, the α values provided in Papers I and II are based on general VSLs that stem from risk contexts in societies other than radiological protection such as: environmental, health and transport risks. The purpose of this approach is to spend financial resources equally between different risk contexts in societies (44,207), based on the view that all lives should be equally valued (208). This approach goes hand in hand with the ICRP's core ethical value of justice (9). It might also lean more towards a hierarchical way of life compared to the α value provided in Paper III, which is based on a VSL derived from people's WTP to avoid, and their WTA, a small risk of radiation-induced cancer death. As it has been shown that people give different VSL estimates for various risk contexts (49,51,65,76–79), arguments for applying context-specific VSL estimates in CBAs have also been made (65,69,189,209). This approach may result in a society being prepared to pay more to save a statistical life from a radiation-induced cancer death compared to preventing deaths from other risks, even when the magnitude of the risks is estimated to be identical. While this situation may appear irrational in a hierarchical way of life, it may simultaneously be perceived as democratic, and thus attractive, within an egalitarian way of life. The approach of applying a context-specific VSL can also be linked to the ICRP's core ethical value of dignity (9). Interestingly, Carlsson et al. (210) reported from their survey that up to one-third of public administrators would prefer to recommend a safety project that increases the general public's sense of security instead of other projects that would in fact save more statistical lives. In contrast, the U.S. Department of Transportation (211) has chosen to use one general VSL estimate in their CBAs, despite acknowledging the fact that VSL estimates usually diverge between airline and road safety.

The stated preference approach of estimating a VSL to be used in an α-value recommendation and applied in a CBA, beautifully connects a quantitative DAT with the ICRP's qualitative recommendation for stakeholder involvement. If the author of this thesis had to recommend one of the α values provided in Table 12 (including Papers I, II and III), it would be an α value based on the stated preference approach of a general VSL. As described above, this approach can be seen as a mixture of hierarchical and egalitarian ways of life, though leaning somewhat more toward the hierarchical side. It reflects the core ethical value of justice, and resources would be allocated equally across different risk contexts. Table 12 only contains five studies published after the year 2000 with α-value recommendations based on the stated preference approach of a general VSL (including Papers I and II). Of these, the α-value recommendations by Kotre (46) and Andresz et al. (75) are within the α-value interval recommended in Paper II. However, the α-value recommendation from the U.S. NRC (74) is higher. Unlike Paper II, the U.S. NRC (74) did not take a discount factor (for future radiation-induced cancer risks) into account when converting their VSL estimate into an α value, which is probably the reason for this disparity. The α values provided in Paper II can be seen as a development of those α values provided in Paper I. In contrast to Paper I, Paper II included productivity losses and healthcare costs. Paper II also developed a superior conversion method (on how to convert societal costs into an α value) compared to Paper I, with an updated risk of exposure and Monte Carlo simulations of the DR and NYEC. Therefore, in accordance with Paper II the author of this thesis would recommend α values of $65-170 per man·mSv for workers (2025 USD), presented as a mean for OECD member states. The most recent international survey conducted by ISOE ETC in 2018 (41) shows that nuclear utilities today apply considerably higher α values, ranging from $890 to $10,000 per man·mSv. These reported α values are also at the high end compared to the other α-value recommendations provided in Table 12.

Finally, a few more comments about α-value recommendations that merit some attention. First, some of the α-value recommendations presented in this thesis were provided as an interval to take the inherent uncertainty in VSL estimates into account. These intervals were interpreted as follows: (i) below the interval was considered a good investment, (ii) within the interval, it was important to consider factors other than cost and collective dose and (iii) above the interval was considered too expensive. In this way, uncertainties of variables in CBAs (such as the collective dose) are unlikely to change the outcome of a CBA between the two endpoints, that is, from a good investment to one that is considered too expensive. Furthermore, the determination of an α value in CBAs is crucial when comparing an investment in radiological protection with the zero option (no further investments). However, the U.S. Department of energy (32) shows in a fictitious example of a CBA that its outcome is not very sensitive to alterations of the α value when different radiological protections options are compared with each other. Finally, the recommended α values provided in Papers I, II and III are applicable to workers. In Paper II, α-value recommendations for the general public are also provided. However, none of these α values are intended for patients, as variations occur in both life expectancy and quality of life between patients, the general public and workers (see further discussion in Section 7.1).

5.6 PEOPLE'S INTERPRETATIONS OF RISKS

With a primary focus on occupational radiological protection, the overall aim of this thesis was to answer the question: How safe is safe enough? In general risk management, several studies (212–215) have claimed that it is not possible to answer this question with a specific number. A very small risk for one individual, for example a fatality risk of 10^{-6} per year, can be considered very serious if 100 million individuals are exposed to the risk each year, that is, 100 fatalities per year (214). However, several authorities and organisations have applied specific numbers to express negligible (or broadly acceptable) risk levels (216,217). For the general public, broadly acceptable risk levels have been stated as between 10^{-5} to 10^{-8} fatalities per year, while for workers the corresponding numbers have been 10^{-4} to 10^{-6} per year (217). The National Council on Radiation Protection (218) stated (in 1993) that an effective dose of 0.01 mSv per year and source should be considered negligible, which they expressed was equal to a fatality risk of 10^{-7}. The ICRP has not recommended a specific negligible dose level, but in 1999 they stated that (25 p.27): 'Under certain conditions, sources used in justified practices can be exempted from regulatory requirements if the individual additional annual doses attributable to the source are below around 0.01 mSv in a year'. They supported this statement by arguing that this dose level represents only a few percent of the annual exposure from natural background radiation, and that the associated annual risk, ranging from 10^{-6} to 10^{-7}, was interpreted to be of no concern (25). The ICRP also reported that natural background radiation contributes only minimally to the overall health risk for the general public, and that exposure at levels comparable to natural background variation is likely to be regarded as acceptable by the general public (15,219). In this context, the ICRP's dose limit for the general public has been set at 1 mSv per year (4,219).

It is worth noting that the disparity in natural background radiation between Denver and Orlando is about 0.7 mSv per year (220). Michel et al. (221) pointed out that this level of exposure is usually not considered a factor when people decide where to live. They concluded that a level of 0.1 mSv per year disappears in the variation of natural background radiation and therefore suggest this level as a lower limit where optimisation is considered unnecessary. An important distinction should also be made between a negligible (or broadly acceptable) risk level and a tolerable risk level. According to Rausand and Haugen (222), a negligible or broadly acceptable risk level can be interpreted as insignificant, while a tolerable risk should be interpreted as a risk level that stakeholders are prepared to take in order to receive a specific benefit. According to the ICRP (15,36), the term ‘acceptable risk’ is interpreted as the risk remaining after exposure has been optimised, whereas a ‘tolerable risk’ refers to exposure that is not optimised but still remains below the specified dose limits.

Cross (223) recognised that people’s ‘misinterpretations’ of small risks derive from their poor understanding of statistics and probabilities. However, Loewenstein et al. (224) concluded that people process small risks both cognitively and emotionally. They pointed out that emotions such as anxiety and fear are shaped by mental images of the risk and are only minimally influenced by changes in the actual smallness of the risk. This circumstance has been called ‘the affect heuristic’ (224,225). Loewenstein et al. (224) also argued that decisions about risks are driven more by emotions than by cognitive processes, leading people to often interpret risks above zero as a source of worry. More broadly, people’s perceptions of risk have been reported to involve more than just the numerical probability (226).

When it comes to risk levels, experts often focus more on the numbers of the risk (a higher degree of cognitive processes) compared to the general public (194,227). Moreover, Nisbett and Ross (228) reported that when people receive new information that confirms their existing beliefs, they tend to place too much trust in it. In contrast, when the new information conflicts with their present beliefs, they tend to dismiss it as unreliable in a too great extent. This has led to some frustration among experts in their attempts to inform the general public about risk levels in different scenarios. As an example, Rasmussen et al. (229) found that 58% of the respondents in their survey were worried about radiation exposure levels that had been acknowledged as safe by an authority. In this context, stakeholder involvement in decision-making is considered a cornerstone of risk management (194,227) and has also been embraced by the ICRP (10).

Based on the author’s experience as a medical physicist, many staff members at Skaraborg Hospital express a strong desire to acquire numerous radiological protection tools. If a CBA shows that these investments are not considered ‘reasonably achievable’ in line with the ALARA principle, some staff members can respond in a confrontational manner. They likely interpret risks through their emotions, with the magnitude of the risks playing a relatively minor role. Moreover, they do not have to pay for these protective tools themselves (consider their own WTP), as it is their employer’s money, which by extension is funded by the taxpayer. In this context, the decision-maker has to balance the recommendation from the medical physicist (the expert opinion) with stakeholder involvement, a balance between a hierarchical and an egalitarian way of life.

5.7 CONSIDERARTIONS REGARDING THE USE OF LEAD APRONS

Section 2.8 outlines a general decrease in occupational exposure within the healthcare system. In addition, Table 13 presents a growing number of publications (including Paper IV) that report a link between pain and the use of lead aprons for long periods of time. Within this context, it is pertinent to address the overall aim of this thesis: How safe is safe enough?

Allowing experts to decide dose levels at which lead aprons and thyroid collars should or should not be used is a hierarchical way of life. The opposite, allowing each staff member to decide for themselves (when exposed below the ICRP dose limits) is an individualistic way of life. Furthermore, trying to achieve some form of consensus among staff about rules regarding lead aprons and thyroid collars can be considered an egalitarian way of life. Paper IV can be seen as an attempt to embrace the egalitarian way of life, in which staff members exposed to ionising radiation were asked for their opinions on wearing lead aprons and thyroid collars. The results show that one-quarter of the respondents reported ache or pain that they believed came from, or was exacerbated by, wearing lead aprons for long periods of time. Moreover, the results also show that three-quarters of the staff would not tolerate an increased future cancer risk from 43% to 43.002% to be able to avoid working with lead aprons. The survey was designed in a way that this alternative was the smallest increased risk presented to the respondents. Considering the discussion in Section 5.6 about people’s interpretations of risks, it is not obvious that a larger proportion of the respondents would tolerate an alternative with an even smaller increase in their future cancer risk. Assuming it is reasonable to define a lower dose limit below which the use of lead aprons is considered unnecessary, regardless of how small that limit might be (a few mSv, a few µSv or a few nSv), it should be noted that the results of Paper IV do not indicate a consensus among staff regarding such a limit. This result highlights one of the weaknesses of the egalitarian way of life: when a group cannot reach consensus, internal conflicts often occur, which are difficult to resolve without an authority (179,180).

In the result of one of the close-ended questions in Paper IV, it turned out that around three-quarters of the staff wanted rules regarding lead aprons and thyroid collars to be decided by an authority (a hierarchical way of life), while the rest thought it should be up to the individual to decide (an individualistic way of life). In summary, Paper IV can be seen as an example of stakeholder involvement (embracing the egalitarian way of life) and highlights some of the obstacles involved in making reasonable decisions about the use of lead aprons and thyroid collars. Even so, considering the reported discomfort associated with wearing lead aprons, the variability of natural background radiation, and the ICRP’s dose limit for the general public, the author of this thesis suggests that: staff should be allowed, but not required, to wear lead aprons for long periods of time when their effective dose is less than 1 mSv per year while working without them. This recommendation can be interpreted as a mixture of hierarchical and individualistic ways of life. The result of Paper IV demonstrates that only one-third of the staff would stop wearing lead aprons (see Figure 6) if this recommendation were to be implemented at Skaraborg Hospital in Sweden.

Table 13. Publications reporting a link between pain and the use of lead aprons for long periods of time. This table is built upon the work: 'Lead aprons and thyroid collars: to be, or not to be?' by Engström et al. (Paper IV), J Radiol Prot, 2023; 43(3):031516, licensed under CC BY 4.0 (2).

Publication	Year	Results
Moore et al. (105 p.191)	1992	'Back pain was reported by 52% of those who estimated their lead apron use at greater than or equal to 10 hr per week, the mean response, as opposed to 46% of those who wore lead aprons fewer than 10 hr a week. These and related results were not statistically significant.'
Ross et al. (106 p.68–69)	1997	'Cardiologists also received more specific therapies (primarily nonsteroidal anti-inflammatory drugs and mechanical support devices) than other physician groups, 52.7% versus 40.5% of orthopaedic surgeons and 31.8% of rheumatologists (p<0.0001).'
Birnie et al. (107 p.957)	2011	'There was a significantly higher prevalence of cervical spondylosis among electrophysiologists compared to matched non-interventional cardiologists (20.7% compared to 5.5%, p=0.033).'
Orme et al. (108 p.822)	2015	'Clinical employees with occupational exposure to procedures involving radiation requiring lead apron use reported experiencing work-related pain more often than the control group (54.7% vs. 44.7%; p < 0.001).'
Andreassi et al. (109)	2016	Exposed workers had a significantly higher prevalence of orthopaedic illness (30.2%) when compared with unexposed subjects (5.4%) p<0.001.
Andrew et al. (110 p.9)	2021	'This study has shown that back pain is more prevalent among staff who regularly used lead aprons (63%) compared to staff who do not (32%).'
Jiang et al. (111)	2022	The interventional cardiologists had significantly higher incidence of body pain (56.6% vs. 24.2%, p<0.001) than the matched non-interventional cardiologists.
Paper IV (p.5)	2023	'For frequent users of lead aprons (>10h/w), 80.0% (95% CI 74.9-85.1%) reported on former or present ache or pain in their neck, shoulders or back. The corresponding proportion for infrequent users (≤10h/w) was 59.% (95 % CI 53.1-65.5%). The absolute difference between these groups was calculated to be 20.7 percentage points (95% CI 5.8-35.6).'

5.8 AN ETHICAL DISCUSSION ABOUT THE FOUR PAPERS INCLUDED IN THIS THESIS

Aristotle’s famous terms ethos, logos and pathos are often considered the origin of ethical considerations (230). Ethos is described as human beings’ ability to judge whether an act is appropriate (right or wrong). Logos concerns human beings’ ability to think and communicate with each other, while pathos is human beings’ ability to affect others’ emotions. The main reason for the popularity of these three terms (first described more than 2,000 years ago) is probably that Aristotle aimed to recognise human beings as they are, not what they should be. These terms are still believed to be valuable within the area of ethical considerations (230).

More recently, the World Medical Association presented the Declaration of Helsinki, which consists of ethical principles for medical research involving human subjects. It was accepted in 1964 and last altered in 2024 (231). It is in itself not a legal document but has often been seen as a cornerstone within ethics and is frequently applied in national legislation (232). The Declaration of Helsinki (231) is based on general principles, such as respecting all human subjects, ensuring that research never stands above the rights and interests of human subjects and conducting studies in a manner that minimises harm to both humans and the environment. In medical research, human subjects should be given information about research aims, methods, funding and the potential risks involved in participation. Furthermore, in the Declaration of Helsinki (231) it is stated that human subjects need to give informed consent to participate in research. In addition, the research can only be performed if the importance of the objective is considered to outweigh the risks and burdens faced by the human subjects. The research also needs approval from the concerned research ethics committee.

The Swedish Act (2003:460) concerning ethical reviews of research involving humans (233) has many similarities with the Declaration of Helsinki. The main purpose of the Act (233) is to: ‘Protect the individual person and the respect for human dignity in research’ (author’s translation). The Act applies to several aspects of research, for example: physical intervention involving participants, methods that physically or mentally can affect research participants, research on biological material that can be traced back to a person and the processing of sensitive personal data (233). The 9 § of the Act (233) states that: ‘Research may be approved only if the potential risks to the health, safety, and personal integrity of research participants are outweighed by its scientific value' (author's translation). Furthermore, the 16 § of the Act (233) states the type of information that must be provided to research participants, such as: the overall research plan, the aim of the research, the methods involved, the consequences and risks for participants, who is responsible for the research, information about the voluntariness of participating and the information that participants can withdraw from the research project at any time. Also, the Act (233) states that the participants need to give their personal informed consent, which should be documented. In this thesis, the main ethical concerns were in Papers III and IV which are based on surveys and include sensitive personal data about health.

In Paper III, the respondents were asked about age, sex, occupation and their overall self-rated health score. In Paper IV, the respondents were asked if they experienced ache or pain (in their neck, shoulders and back) that they believed came from or was exacerbated by wearing lead aprons at work. In both Papers III and IV the respondents received information about the increased risk of radiation-induced cancer from being exposed to ionising radiation at work. To mitigate potential stress from receiving this information, respondents were provided with the contact details of a medical physicist. This allowed them to seek further information or address any concerns after participating in the study; however, none of the respondents made use of this option. Furthermore, Papers III and IV adopted an essentially inductive approach, with the aim of observing and interpreting staff members' willingness to pay (WTP) to avoid a small risk of radiation-induced cancer death (Paper III), and their willingness to tolerate a small increase in future cancer risk to avoid wearing lead aprons (Paper IV). However, Paper IV also included some hypothesis testing (a deductive point of view), where staff members' willingness to tolerate an increased future cancer risk to avoid wearing lead aprons was tested for significant differences between occupations and sexes. Nevertheless, as described above, Papers III and IV were essentially seen as inductive studies and therefore the goal was to collect the number of answers needed to achieve saturation. In reality, as many answers as possible were gathered with the available financial resources. In Paper III, the survey was sent by email to 4,680 employees who were exposed to ionising radiation at their workplace in Region Västra Götaland. Answers were received from 718 of them, a response rate of 15%. In Paper IV, the survey was handed out to staff at Skaraborg Hospital immediately before their radiation safety education. Despite information about the voluntariness of participation in the study, the employees in this situation can be described as a captive group, with a higher degree of feeling obligated to participate compared to those in a survey distributed by email. A captive group usually results in a high response rate (234) and in Paper IV answers were collected from 245 respondents corresponding to a response rate of 96%. Both Paper III (No. 2022-04593-01) and Paper IV (No. 2021-03027) received ethical approval from the Swedish Ethical Review Authority. The risks to the research participants (storing their sensitive personal information about health and the possible risk of causing them distress due to informing them about an increased risk of radiation-induced cancer) were considered to be counterbalanced by the scientific value of the studies. All respondents in Papers III and IV provided their informed consent to participate.

In Paper III, the number of invited participants (employees in Region Västra Götaland exposed to ionising radiation) was initially estimated at approximately 3,800, as specified in the application for ethical approval (No. 2022-04593-01). However, it was later established that the actual number of eligible employees, excluding medical physicists, was closer to 4,680. In order to be able to invite all of them to participate in the study, an update of the ethical approval application was required. The Swedish Ethical Review Authority had to assess the risks due to the new number of possible participants in relation to the scientific value of the study. The Swedish Ethical Review Authority also approved the extended application (No. 2023-03506-02).

In Paper I, cases of CBAs in occupational radiological protection were presented. In this study, staff members' exposure to ionising radiation was extracted from a register at Skaraborg Hospital (Sweden), but only at group level. To ensure that the plan for handling the research data was appropriate, an application was submitted to the Swedish Ethical Review Authority. The authority waived to review the application (No. 2021-00320), stating that the research did not involve any sensitive personal information and therefore not subject to 3-4 §§ of the Swedish Act (2003:460) concerning ethical review of research involving humans (233).

Paper II was based on already published data about VSL, productivity losses from premature cancer deaths and lifetime healthcare costs associated with cancer. By means of these already published data, a method for converting societal costs into an α value and new α-value recommendations for each OECD member state were presented. Consequently, Paper II did not involve any new research on human subjects, thus did not require ethical approval from the Swedish Ethical Review Authority.

6 SUMMARY AND CONCLUSIONS

In the short term, a society's resources are limited, therefore making the prioritisation of needs unavoidable. For instance, the more financial resources a hospital allocates to radiological protection, the fewer remain available for other healthcare needs. With a focus on occupational radiological protection, the overall aim of this thesis was to answer the question: How safe is safe enough? To fulfil the overall aim, this thesis had a primary focus on development and implementation of CBA within occupational radiological protection, but also on promoting stakeholder involvement regarding decisions about the use of lead aprons and thyroid collars for long periods of time.

Using different health economics techniques and assumptions, Papers I, II and III all provided different α-value recommendations. In Paper I, the α-value recommendation useful for occupational radiological protection in Sweden was determined to be between \$45 and \$450 per man·mSv (2021 USD). This interval was interpreted as follows: (i) below the interval was considered a good investment, (ii) within the interval, it was important to consider factors other than cost and collective dose and (iii) above the interval was considered too expensive. This α-value recommendation was based on VSL estimates drawn from Swedish society, primarily related to transport risks (43). In Paper II, recommended α values were based on VSL estimates from a meta-analysis of studies from OECD member states in the context of environmental, health and transport risks (64). These VSL estimates were adjusted for time as well as for Sweden's economic status compared to other OECD member states and converted into α values. The recommended α values were between \$57 and \$171 per man·mSv for the Swedish general public and between \$62 and \$163 per man·mSv for Swedish workers (2023 USD). The recommended α values for Swedish workers presented in Paper II are well within the interval of recommended α values in Paper I. In Paper III, an α-value recommendation for Swedish workers of \$1,600 per man·mSv (2024 USD) was provided. In contrast to Papers I and II, the recommendation in Paper III was based on a different approach, namely a survey in which staff exposed to ionising radiation at work were asked about their WTP to avoid, and their WTA, a small risk of radiation-induced cancer death.

The α-value recommendations in this thesis (Papers I, II and III) were based on different health economics techniques and assumptions, and therefore, the discrepancy between them is not surprising. These recommendations can also be interpreted to stem from different points of view (different ways of life) in line with cultural theory (177,179). All three papers were based on VSLs from the stated preference approach, which can be seen as a mixture of hierarchical and egalitarian ways of life. However, in Papers I and II the recommended α values were derived from general VSL estimates, which leads to a situation where a society's financial resources are equally distributed between various risk contexts. Therefore, Papers I and II can be seen as leaning somewhat more toward the hierarchical way of life and emphasizing the ethical core value of justice. In contrast, Paper III, which based its α-value recommendation of a specific VSL estimate from radiological protection, reflects a more egalitarian way of life and prioritises the ethical core value of dignity. In this context, a situation can occur where a society's financial resources are mostly spent on those risks that its citizens fear most, despite the fact that the magnitude of the various risks is estimated to be identical.

If the author of this thesis were asked to recommend one of the provided α values in this thesis, the preference would be for the hierarchical way of life, the core ethical value of justice, and the α-value recommendations in Paper II. In this way, all lives would be valued equally. The α-value recommendations in Paper I would be rejected because those in Paper II can be seen as a development of them. However, as it is the responsibility of each licensee's operating management to comply with the ALARA principle, it is also up to them to decide on an appropriate α value for their organisation to use when employing a CBA (10). The author of this thesis argues that requiring the licensee to determine an α value places an unnecessarily burdensome and complex responsibility on them. Therefore, the author urges the ICRP and national radiation safety authorities to provide stronger statements about α-value recommendations for each country. A factor of eight has been reported between the lowest and highest α values applied by nuclear utilities within the U.S. (41), and such substantial discrepancies are unnecessary. Furthermore, the α values applied by nuclear utilities today (41) are at the high end compared to those recommended in this thesis as well as by other publications, see Table 12.

In addition to recommending α values, Paper I also reports seven cases of CBAs in occupational radiological protection within the Swedish healthcare system. These cases illustrate how CBAs can be implemented as well as showing a substantial disparity in costs per saved collective dose from different tools used in occupational radiological protection. For example, radiation protection gloves cost $3.7 million per saved man·mSv, which is considered too expensive, whereas lead aprons in nuclear medicine cost only $130 per saved man·mSv, indicating that factors beyond cost and collective dose are also important to consider. Paper II also presents the development of a new conversion method for how to convert societal costs into an α value. By means of Monte Carlo simulations the new conversion method was presented as the discounted nominal risk of exposure of 175 per 10,000 persons per Sv for the general public and 169 per 10,000 persons per Sv for workers.

The ICRP identifies stakeholder involvement as an important tool for working with the ALARA principle (10). In Paper IV, this approach was implemented by asking staff exposed to ionising radiation at work about discomfort associated with wearing lead aprons and thyroid collars for long periods of time. They were also asked about their willingness to tolerate a small increase in their future cancer risk to avoid wearing these protective tools. The results show that discomfort among staff was common: one-quarter reported ache or pain that they believed came from, or was exacerbated by, wearing lead aprons for long periods of time. On the other hand, three-quarters indicated they would not tolerate even a minimal increase in their future cancer risk (from 43% to 43.002%) in order to avoid wearing lead aprons. These results highlight the complexity of making reasonable decisions (in accordance with the ALARA principle) about wearing lead aprons and thyroid collars for long periods of time. Even so, considering the reported discomfort associated with wearing lead aprons, the variability of natural background radiation, and the ICRP's dose limit for the general public, the author of this thesis suggests that: staff should be allowed, but not required, to wear lead aprons for long periods of time when their effective dose is less than 1 mSv per year while working without them.

To conclude, the author would like to provide two take home messages from this research field. First, as stated by the ICRP (4 p.92, 10 p.73): 'The best option is not necessarily the one with the lowest dose'. And second, which illustrates the complexity of it all, the statement in Paper IV (p.9) referring to the work by Loewenstein et al. (224): 'When a risk is estimated to be above zero it becomes a source of worry, and variations in the smallness of the risk have little emotional impact'. Finally, the author hopes that this thesis contributes one piece to the broader puzzle of occupational radiological protection and offers some answers to the overall question: How safe is safe enough?

7 FUTURE PERSPECTIVES

During the work with this thesis many thoughts and ideas crossed the author's mind. Some were excellent, some were decent, and others were downright bad. In this section some thoughts and ideas about future work within this research field are presented.

7.1 FORTHCOMING COST-BENEFIT ANALYSIS

This thesis has mainly focused on CBAs in occupational radiological protection within the healthcare system. A future step would be to develop and implement CBAs that are useful for patients. To the best of the author's knowledge, only a couple of papers have been published on this topic (44–47). The main barrier involves the development of solid α-value recommendations, bearing in mind that patients are unwell (have a lower quality of life and lower life expectancy) compared to both the general public and workers. Patients are also typically older than both the general public and workers, which in turn indicates a lower life expectancy. One way to provide a solid α value for patients is to ask them to fill in a survey based on the stated preference approach of VSL immediately after undergoing an X-ray examination. The survey could ask how much they are willing to pay to be examined by means of a new X-ray machine with a specified lower risk of future radiation-induced cancer the next time they need an examination. Such a study would provide an opportunity to show whether or not new X-ray machines would be profitable on a theoretically free market, where patients pay the full cost of their examinations. Using a determined α value for patients (from this future study), along with the estimated effective dose reduction and the cost of new X-ray machines, CBAs could determine whether investing in new X-ray machines would be justified from a health economics perspective. It is worth noting that different patient groups, with varying characteristics and examined using different X-ray machines, may yield different VSL estimates and, consequently, different α values. Furthermore, newer X-ray models may offer improved diagnostic capabilities (like enhanced spatial resolution) compared to older models, a factor not accounted for in the above reasoning.

Another way of providing a solid α value for patients would be to convert a general VSL from the general public to an α value for patients. This could be performed in a similar way as outlined in Paper II, by considering dissimilarities between the two groups in their nominal risk of exposure, NYEC, productivity losses and remaining number of QALYs. In this context, it is worth bearing in mind the discussion about age-dependent VSL mentioned in Section 5.4. If (from a political point of view) a general VSL is desired that is independent of both life expectancy and quality of life, then a general α value for both the general public, workers and patients might also be desirable.

7.2 FUTURE STUDIES ON LEAD APRONS

To the best of the author's knowledge, only one systematic literature review has been published (235) about the potential correlation between back pain and wearing lead aprons for long periods of time. This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines and included twelve studies in its qualitative synthesis. The conclusion of this review was that (235 p.1): 'There is no complete agreement about the correlation between anti-X apron-wearing and the occurrence of musculoskeletal disorders, although the possible discomfort of workers using anti-X aprons appears more evident'. After reading these twelve studies, the author of this thesis did not fully agree with their conclusions. Instead, the results (together with findings from three additional studies) were interpreted as reported in Paper IV (p.8): 'Publications […] show a growing body of evidence between pain and working with lead aprons for long periods of time'. A similar conclusion (partly based on the same studies) has previously been published by Dixon et al. (112). In this context, it would be beneficial to conduct a new systematic literature review in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines, to determine whether the statement from Paper IV is valid.

Furthermore, most lead aprons are designed with 0.5 mm, 0.35 mm or 0.25 mm lead equivalent material. In the literature, the author only found two studies (161,236) that compared the investment cost of lead aprons with their collective dose savings by means of a CBA. In 2001, Lambert and McKeon (236) concluded by the means of a CBA that a defect in a lead apron needs to be larger than 15 mm^2 before it should be replaced. In 1988, Russell and Hufton (161) concluded that for the average radiologist a 0.35 mm lead apron is considered a good investment, but for an interventional radiologist a 0.5 mm lead apron is preferable. Since then, a notable decrease in occupational exposure has been reported (115–117). Therefore, in Paper I the authors reported that about one-quarter of the lead aprons used at Skaraborg Hospital within cardiology and interventional radiology could be considered too expensive when comparing the investment costs with their collective dose savings. In future studies, not only the investment costs should be compared to the collective dose savings but also the number of QALYs lost due to an increased risk of developing back pain or exacerbating an existing back problem when wearing lead aprons for long periods of time. If possible, the number of QALYs lost from an increased risk of back pain due to wearing lead aprons could be balanced against the number of QALYs lost from an increased risk of radiation-induced cancer by not wearing them. Another future study could be to apply the same methodology as in Paper IV (and promoting stakeholder involvement) by allowing staff members to wear lead aprons with different levels of lead equivalent materials and thereby different weights. Staff members could then be asked which lead apron they prefer, based on its weight, level of radiation protection, and the resulting risk of radiation-induced cancer.

As mentioned in Section 2.8, an interesting study about lead aprons was published by Huda and Boutcher (123) in 1989. They investigated the effective dose savings in relation to the time spent wearing lead aprons for different diagnostic examinations in nuclear medicine, in what they called an apron-time efficiency parameter. Unfortunately, their conclusion was somewhat unsatisfactory, as they left it up to the nuclear medicine technologist to decide in which the diagnostic examinations they should wear lead aprons. It would be interesting to conduct a similar study in radiology at present levels of exposure. It might be possible to make a recommendation about an acceptable level of exposure in relation to the time spent wearing a lead apron. If so, wearing a lead apron could become optional during some X-ray guided procedures. If such a recommendation were implemented in a hospital, it would be interesting to examine the proportion of staff who would actually stop wearing lead aprons, in relation to the survey results reported in paper IV. A somewhat different approach would be to work more with free-standing mobile lead shields instead of wearing lead aprons. For example, in 2021 Roelz and Hubbe (237) reported that they had ‘unleaded’ spinal surgery at the hospital in Freiburg (Germany), as they started to use free-standing mobile lead shields.

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