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Potential occupational exposures in diagnostic and interventional radiology – statistical modeling based on Finnish national dose registry data

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Abstract

Background

Radiation worker categorization and exposure monitoring practices must be proportional to the current working environment.

Purpose

To analyze exposure data of Finnish radiological workers and to estimate the magnitude and frequency of their potential occupational radiation exposure, and to propose appropriate radiation worker categorization.

Material and Methods

Estimates of the probabilities of annual effective doses exceeding certain levels were obtained by calculating the survival function of a lognormal probability density function (PDF) fitted in the measured occupational exposure data.

Results

The estimated probabilities of exceeding annual effective dose limits of 1 mSv, 6 mSv and 20 mSv were in the order of 1:200, 1:10 000 and 1:500 000 per person, respectively.

Conclusion

It is very unlikely that the Category B annual effective dose limit of 6 mSv could even potentially be exceeded using modern equipment and appropriate working methods. Therefore, in terms of estimated effective dose, workers in diagnostic and interventional radiology could be placed into Category B in Finland. Current national personal monitoring practice could be replaced or supplemented using active personal dosimeters, which offer more effective means for optimizing working methods.

Keywords

Occupational/Environmental Hazards; Radiation Safety; Interventional; Fluoroscopy

Introduction

During the last 10–20 years, the transition to digital imaging equipment and other advances in imaging technology have reduced occupational radiation exposures per procedure in the fields of diagnostic and interventional radiology. Improved working methods and growing awareness of the importance of protocol optimization have also led to a reduction in worker exposures per procedure. Despite more rigorous assessment of the justification for diagnostic and interventional x-ray exposures, the number of radiological examinations and interventional procedures has increased in Finland during 2011–2015 (1), due to the increased clinical demand for diagnostic and interventional x-ray procedures. The use of fluoroscopy has also expanded outside of radiological imaging departments in, for example, interventional cardiology (2). The growing numbers of x-ray examinations affects the radiation exposure of staff. The combined effect of changing practices on occupational exposures is difficult to predict accurately. Nevertheless, knowledge of the occupational exposure levels of different worker groups must be obtained before appropriate monitoring and protection measures can be determined and implemented for each group.

Radiation protection regulations and guidelines are based on international standards and recommendations such as the International Commission on Radiological Protection (ICRP) recommendations (3) and the International Atomic Energy Agency (IAEA) Basic Safety Standards (4). In the European Union Member States, radiation protection is mainly regulated by the appropriate European Council Directives. In 2013, the EU published the Council Directive (2013/59/Euratom) (5) which describes the basic safety standards (EU BSS) for ionizing radiation that are to be implemented in EU Member States by February 2018. The classing of workers into A and B categories on the basis of expected or potential work-related radiation exposure levels is maintained in the new EU BSS. Workers who may be exposed to an effective dose of over 6 mSv per year, or an equivalent dose of over 15 mSv per year for the lens of the eye, or over 150 mSv per year for skin and extremities are placed in Category A. It must be noted that even though, on the basis of Article 40 of the EU BSS, worker categorization must account for potential exposure in unexpected situations such as equipment failure or operating errors, the EU BSS provide no exact guidance on how to account for the probabilistic nature of these events or the tolerated risk of exceeding the categorization values.

According to the European Commission's technical recommendations (6), workers' occupational radiation doses are monitored by measuring personal dose equivalent quantities $H_p(10)$ for depth dose, and $H_p(0.07)$ for shallow dose. Thermoluminescent dosimeters (TLDs) or active personal dosimeters (APDs) are commonly used to measure these quantities. According to national practice, the dosimeter is placed outside the protective lead apron (7). The task of estimating effective doses based on dosimeter readings using Monte Carlo simulations has been studied previously (see e.g. (8-10)). Dosimeter readings measured outside a lead apron have been reported to overestimate the effective dose by a large margin, necessitating the use of a conversion factor between the two quantities. Based on the Monte Carlo simulations of different plausible exposure conditions, Siiskonen et al. (8) concluded that a 1/30 conversion factor should overestimate the effective dose by a factor of two when a lead apron is used, and a factor of four when a thyroid shield is used in addition to a lead apron.

Annual occupational effective doses for workers in the field of radiology have been previously estimated (11-16). Kortesniemi et al. estimated the likelihood of occupational exposures of certain magnitude using probabilistic modeling based on measured exposure data. Based on the analysis of cumulated five-year personal dose monitoring data of 267 workers, exceeding the annual Category B limit of 6 mSv effective dose was concluded as being very unlikely. The probability of exceeding the categorization limit was estimated to be in the order of 1:20 000, which suggests that these workers could all be moved to Category B (14).

The first aim of this study was to estimate the probability of the annual effective dose exceeding certain levels for different radiological worker groups in Finland. This was achieved by analyzing annual personal exposure data from the national occupational dose registry from the last 20 years. The second aim was to discuss the implications of these estimates and to propose revised categorization and monitoring practices for diagnostic and interventional radiology.

Material and Methods

The data analyzed in this study was provided by the National Radiation and Nuclear Safety Authority of Finland (STUK). The anonymous data set consisted of personal TLD readings measured outside the protective lead apron, at chest height. The TLDs were calibrated for $H_p(10)$ by the measurement service provider. The data covered all Finnish radiation workers wearing personal dosimeters in radiology from 1996 to 2015, which made a total of 80 761 annual personal dose entries. The personal dose records could not be followed through the years. In the data set, we categorized workers into different groups according to their role, so that any given worker was only included in a single group during a certain year. In addition to radiologists, the data set also included groups for cardiologists, orthopedists, other physicians, radiographers and nurses. The radiologists who performed fluoroscopical procedures regularly were listed in their own separate group as interventional radiologists. Physicians such as some surgeons and residents who were not part of any of the other groups, but still used ionizing radiation in procedures, were classified as other physicians. The occupational data from the most recent decade (2006–2015) mostly corresponded to that of modern digitalized x-ray imaging technology and current working methods. Table 1 shows the number of annual dose register entries (person-years) for the last decade, provided by the national dose register.

We transformed the annual personal dosimeter readings into estimated effective dose values using a conversion factor of 1/30 (8). A constant conversion factor was used for all worker groups and for all years. The dependence of the results on the conversion factor was tested by performing a sensitivity analysis using conversion factors of 1/60, 1/30, 1/20 and 1/10 between dosimeter readings and estimated effective doses. We performed the analysis on interventional radiologists, who are the most exposed worker group. The dose recording threshold in Finland is 0.1 mSv per month (measured outside the protective apron). Dosimeter readings below this limit are recorded as zero. Only non-zero estimated effective dose values from 2006–2015 were included in the data set used for distribution fitting and probabilistic modeling. The non-zero estimated effective dose values were first transformed into histogram form. The lognormal distribution, which several previous publications (17-19) have applied to model occupational exposure data, was selected as the model of choice for distribution fitting. We fitted probability density functions (PDFs) to the histograms, and the estimated probabilities of the effective dose exceeding certain selected annual levels were then calculated as survival function values based on the fits. Finally, we compared the estimates to probabilities calculated directly from the measured data. These steps were performed for all worker groups separately, as well as for all workers as a single group.

Although the main purpose of this article is to estimate effective dose, it also crudely estimates the equivalent dose to the lens of the eye from measured $\mathrm{H_p}(10)$ values (20). Based on the literature (21-24), a conversion factor of $0.8 \times \mathrm{H_p}(10)$ for measurements outside the apron may be applied for the lens equivalent dose when protective eyewear is not used. Workers with the highest exposure routinely wear protective glasses, lowering the eye lens dose by 60 – 80% (25,26). To account for the effect of protective glasses, a conversion factor of $0.8 \times 0.4 = 0.32$ could thus be used between $\mathrm{H_p}(10)$ and eye lens equivalent dose. However, it must be acknowledged that the estimation of the eye lens dose based on dosimeter readings measured at chest height is considerably uncertain.

Results

Mean and maximum values for annual estimated effective doses in the last 20 years for all worker groups are presented in Figure 1 a-b. The estimated effective dose data used in the probabilistic modeling is shown in histogram format in Figure 2. This data set contains all non-zero dosimeter readings for all worker groups in 2006–2015.

Figure 3 shows the histogram of annual estimated effective doses for all workers in the last 10 years and the fitted lognormal PDF. Both the histogram and the fitted PDF are normalized to unitary area.

The estimated probabilities of exceeding certain annual effective dose levels are listed in Tables 2 a-h for all worker groups. Tables 2 a-h also include the probabilities calculated directly on the basis of the measured data, both with and without the exposures recorded as zero. The results of the conversion factor sensitivity analysis are shown in Figure 4.

The estimated probabilities of interventional radiologists exceeding certain annual eye lens equivalent dose levels are presented in Tables 3 a-b. To take into account the effect of using protective glasses, the probabilities were calculated using conversion factors of 0.32 and 0.8 between the dosimeter reading and the eye lens equivalent dose.

Discussion

This study determined actual and potential occupational radiation exposures in diagnostic and interventional radiology on the basis of the data obtained from the national dose registry. We found no annual estimated effective doses over the 6 mSv Category B limit in the last 10 years of data. During the last 20 years, the limit has only been exceeded on two occasions, in 1996 and 1997, both times by an interventional radiologist. Given the size of the data set, the lack of high exposures indicates that the probability of events in which a radiological worker would receive an abnormally large radiation dose due to an unforeseen event, such as equipment malfunction, is minimal in the case of Finnish radiological workers. When modern imaging equipment is used with appropriate working methods and quality assurance protocols, this should always be the case. The actual occurrence of exposures during the two decades (Fig. 1 a-b) in terms of mean and maximum annual estimated effective dose shows slightly declining or stable levels as a function of time for all worker groups, except for the radical decline among interventional radiologists between 1997 and 1999. During this period, new interventional radiologists with modernized radiation protection and procedure optimization training entered the field, lowering the mean annual estimated effective dose. With an increasing number of interventionists, the exposure from procedures was distributed more evenly among the relatively few interventional radiologists in Finland, which reduced the maximum annual estimated effective dose.

The notable influence of the differences in working methods on occupational radiation exposures highlights the importance of educating personnel on radiation protection, especially those who perform a great deal of fluoroscopical procedures. Currently, operational staff are aware of the magnitudes of exposures in typical exposure settings, partly due to the expanding use of electronic dosimeters in personnel training. However, there are still considerable inter-operator differences in radiation dosages, which arise from the varying working habits of the interventional x-ray operators. Such human variability cannot be totally overcome, and it is combined with the notable variability of exposures based on the type of intervention and individual settings such as the complexity of each intervention due to individual patients. Other factors may also explain the changes in occupational exposures over time. X-ray equipment was updated from previous technology by incorporating new dose saving options such as pulsed exposure, increased x-ray beam filtration, more sensitive image detectors and improved automatic exposure control systems. Such optimization tools have reduced the radiation exposure of both patients and interventional staff. In the evolving digital era, the image post-processing algorithms have further enabled the utilization of a lower number of x-ray quanta per image frame, without degrading clinical image quality.

We made several approximations when calculating the probability estimates included in this article, and it must be stressed that the probability values presented as a result of this analysis have considerable uncertainties. However uncertain, these estimates are useful if they can be used as worst-case values, that is, even if they overestimate the likelihood of high occupational exposures. For this reason, the approximations made were chosen to consistently overestimate the annual effective dose. The 1/30 conversion factor used in converting the annual $H_p(10)$ dosimeter readings to annual effective doses overestimated the effective dose by a factor of two or more (8). To account for the use of a thyroid shield in addition to a lead apron, a conversion factor of 1/60 would be more appropriate, reducing the estimated effective doses to operators by half. The effective dose conversion factor of 1/30 has been used as a safe overestimate. Another approximation is the lognormal fit, which overestimated the probabilities of annual effective doses in the range of 1 mSv and above for all worker groups when compared to measured values. The deviation from lognormal distribution was at its greatest for interventional radiologists and cardiologists, which are the two groups with the highest mean and maximum exposures.

Dosimeter readings corresponding to an annual estimated effective dose of 2 mSv and above have not been recorded in the last 10 years among radiological workers in Finland. Thus, the lognormal distribution fitting was conducted on the basis of frequencies of lower exposures, and the distribution was then extrapolated to higher doses to produce the probability estimates for the higher exposures. Therefore, the results of our probabilistic modeling for high effective doses contain the assumption that the frequency of exposures follows the same distribution regardless of dose level. This excludes the hypothetical occurrence of intentional (malevolent) acts of exposures, which do not belong to the category of occupational exposures. Moreover, if high dosimeter readings were encountered in the actual practice, corrective actions would be in place to reduce the exposure. The tendency of lognormal distribution to overestimate the likelihood of high exposures when dose monitoring and corrective actions are in place has also been previously reported (18).

The statistical methodology of this study means that the recorded zero exposures were not used for the probabilistic modeling. Furthermore, although the dose registry included data from two decades, this study focused on the more recent decade (years 2006–2015) for the distribution fitting and calculation of probability estimates. Due to these two exclusions, the size of the data set was reduced to 5985 person-years from the 80 761 person-years of the entire data set. Zero values were excluded due to the statistical method to ensure that the probabilities were not underestimated due to the inclusion of workers who did not participate in interventional procedures, or only wore the dosimeter for a short period of time. The removal of zero doses places extra weight on the higher exposures, which is desirable when trying to establish worst-case estimates. We decided to only use the data from last 10 years, as the recent decade’s exposure data more truthfully represent the current state of the practice, considering that imaging technology, working methods and exam volumes have evolved considerably in recent years.

Based on both the measured exposures and the probability estimates, exceeding the Category B limit of 6 mSv effective dose per year is unlikely for a radiology worker. For all workers, the worst-case annual probability estimate of 6 mSv is approximately 8:100 000 per person. The highest probability estimate is 7:1000 per person for interventional radiologists. The sensitivity analysis in

Figure 4 shows that even overestimating the estimated effective dose by using a conversion factor of 1/10 would not place any workers in Category A on the basis of the measured exposures. It is emphasized that the lognormal model, which in this study considers only the lower-dose non-zero data bins, provides a significant overestimate of the higher dose potential probabilities, for example the 0.7% for 6 mSv exposure among interventional radiologists. If the lognormal model also accounted for the zero data bins, the potential exposure probability would be significantly lower in the higher dose range, with no real registered occurrences. This aspect is also clearly shown when comparing the dose data (based on the registered occurrences) to lognormal fit probabilities in Tables 2a to 2h, while also taking into account the number of annual dose data entries in Table 1.

With the lowering of eye lens equivalent dose Category B limit from 150 mSv to 15 mSv per year (5), the limiting factor for categorization may potentially be the lens dose, rather than the effective dose. Our estimated lens equivalent doses for interventional radiologists with a conversion factor of 0.32 showed no instances of estimated lens equivalent doses over the Category B limit of 15 mSv/year. The lognormal fit predicted a 6% change for an interventional radiologist to exceed 15 mSv/year and 4% to exceed 20 mSv/year. It is likely that the lognormal fit overestimated the probabilities. Assuming no use of protective glasses and estimating by using the conversion factor of 0.8 results in several interventionists exceeding 15 mSv/year, and even 20 mSv/year. Studies by Ingwersen et al. (15) and Dauer (28) have reported annual lens doses over 15 mSv among interventional radiologists who do not use protective glasses and shields. Although other studies (16,29) have reported smaller estimates, these observations highlight the importance of protecting the eyes for the most exposed workers. Even with adequate protection, the new eye lens dose limit could place these workers in Category A. Further studies on eye lens doses with more suitable dosimetry are required for a more accurate assessment of lens dose levels.

Placing most radiology workers into Category B would permit changes in monitoring practices. In the future, individual TLDs could be replaced by APDs used by the most exposed operators. By utilizing the real-time feedback given by APDs, working methods could be optimized more efficiently. High exposure rate situations could be detected as they happen, enabling corrective action to be taken immediately, which would further reduce potential radiation exposures. We emphasize that special care must be taken to protect the eyes of radiologists and cardiologists who perform a great deal of fluoroscopical procedures. The suggested means of protection include the use of protective lead glasses during all procedures and ceiling-suspended lead shields when possible. Category A classification could be considered for the most exposed interventional radiologists performing a high number of procedures with potentially prolonged duration of fluoroscopy use. This exception would be more related to the possible exceeding of the eye lens equivalent dose limit than to the effective dose limit. For such Category A workers, APDs in addition to personal dosimeters would bring a clear additional benefit by providing real-time exposure information.

In conclusion, we note that, based on our analysis, exceeding the 6 mSv annual effective dose category B limit is unlikely for any radiological worker group in Finland, including interventional radiologists and cardiologists. Therefore, we conclude that in terms of annual effective dose, radiation workers could be placed into Category B in radiology. Current Finnish personal monitoring practice could be replaced or supplemented by the use of active personal dosimeters, offering more effective means of optimizing working methods.

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Tables

Table 1: Number of annual dose register entries (person-years) for each group of workers from 2006 to 2015

Worker group	Total number of person-years, all workers	Person-years, workers with recorded exposure
Radiographers	17851	1139
Nurses	10575	1098

Radiologists	4301	1023
Other physicians	3950	813
Cardiologists	1930	1617
Orthopedists	461	43
Interventional radiologists	296	252
All groups 2006–2015	39364	5985

Table 2a: All workers

Yearly effective dose (mSv)	Probability: lognormal fit	Probability: non-zero data	Probability: full data set
0.1	1:6	1:5	1:29
0.5	1:48	1:56	1:357
1.0	1:175	1:769	1:5000
3.0	1:2041	0	0
6.0	< 1:12 000	0	0
10.0	< 1:50 000	0	0
20.0	< 1:500 000	0	0
100.0	< 1:10^8	0	0

Table 2b: Radiologists

Yearly effective dose (mSv)	Probability: lognormal fit	Probability: non-zero data	Probability: full data set
0.1	1:5	1:4	1:17
0.5	1:40	1:63	1:270
1.0	1:152	0	0
3.0	1:2083	0	0
6.0	< 1:14 000	0	0
10.0	< 1:70 000	0	0
20.0	< 1:800 000	0	0
100.0	< 1:10^8	0	0

Table 2c: Cardiologists and interventional cardiologists

Yearly effective dose (mSv)	Probability: lognormal fit	Probability: non-zero data	Probability: full data set
0.1	1:3	1:2	1:3
0.5	1:20	1:50	1:53
1.0	1:77	0	0
3.0	1:1220	0	0
6.0	< 1:10 000	0	0
10.0	< 1:50 000	0	0
20.0	< 1:900 000	0	0
100.0	< 1:10^9	0	0

Table 2d: Interventional radiologists

Yearly effective dose (mSv)	Probability: lognormal fit	Probability: non-zero data	Probability: full data set
0.1	1:2	7:10	1:2
0.5	1:5	1:5	1:6
1.0	1:10	1:36	1:42
3.0	1:43	0	0
6.0	1:145	0	0
10.0	1:400	0	0
20.0	1:1887	0	0
100.0	< 1:150 000	0	0

Table 2e: Orthopedists

Yearly effective dose (mSv)	Probability: lognormal fit	Probability: non-zero data	Probability: full data set
0.1	1:20	1:14	1:154
0.5	1:1538	0	0
1.0	< 1:20 000	0	0
3.0	< $1:10^6$	0	0
6.0	< $1:10^8$	0	0
10.0	< $1:10^9$	0	0
20.0	< $1:10^{11}$	0	0
100.0	< $1:10^{16}$	0	0

Table 2f: Other physicians

yearly effective dose (mSv)	Probability: lognormal fit	Probability: non-zero data	Probability: full data set
0.1	1:7	1:6	1:26
0.5	1:100	1:135	1:667
1.0	1:500	1:833	1:3333
3.0	< 1:10 000	0	0
6.0	< 1:110 000	0	0
10.0	< 1:700 000	0	0
20.0	< $1:10^7$	0	0
100.0	< $1:10^{10}$	0	0

Table 2g: Radiographers

Yearly effective dose (mSv)	Probability: lognormal fit	Probability: non-zero data	Probability: full data set
0.1	1:263	1:227	1:3333
0.5	1:300 000	0	0
1.0	< $1:10^7$	0	0
3.0	< $1:10^{10}$	0	0
6.0	< $1:10^{13}$	0	0
10.0	< $1:10^{15}$	0	0
20.0	< $1:10^{16}$	0	0
100.0	< $1:10^{16}$	0	0

Table 2h: Nurses

Yearly effective dose (mSv)	Probability: lognormal fit	Probability: non-zero data	Probability: full data set
0.1	1:145	1:110	1:1111
0.5	< 1:80 000	0	0
1.0	< $1:10^6$	0	0
3.0	< $1:10^9$	0	0
6.0	< $1:10^{11}$	0	0
10.0	< $1:10^{13}$	0	0
20.0	< $1:10^{15}$	0	0
100.0	< $1:10^{16}$	0	0

Table 3a: Estimates of eye lens equivalent dose, Conversion factor = 0.32, interventional radiologists

Yearly lens equivalent dose (mSv)	Probability: lognormal fit	Probability: non-zero data	Probability: full data set
0.1	97:100	92:100	78:100
0.5	77:100	79:100	68:100
1.0	3:5	7:10	3:5
5.0	1:5	1:5	1:6
10.0	1:10	1:63	1:74
15.0	1:17	0	0
20.0	1:25	0	0
100.0	1:439	0	0

Table 3b: Estimates of eye lens equivalent dose, conversion factor = 0.8, interventional radiologists

Yearly lens equivalent dose (mSv)	Probability: lognormal fit	Probability: non-zero data	Probability: full data set
0.1	99:100	98:100	83:100
0.5	91:100	86:100	73:100
1.0	81:100	81:100	69:100
5.0	9:20	12:20	10:20
10.0	1:4	1:4	1:5
15.0	1:6	1:7	1:8
20.0	1:8	1:17	1:20
100.0	1:75	0	0

Figure legends

Fig. 1a: Mean annual effective dose for each worker group during 1996–2015

Fig. 1b: Maximum annual effective dose for each worker group during 1996–2015

Fig. 2: Histogram of annual effective doses for all workers during 2006–2015. Dose registry entries recorded as zero have been removed from the data.

Fig. 3: Normalized histogram and fitted lognormal PDF of annual effective doses for all workers during 2006–2015. Dose registry entries recorded as zero have been removed from the data.

Fig. 4: Sensitivity analysis: Effective dose level probabilities for interventional radiologists with different conversion factors between dosimeter reading and effective dose.