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ACTUAL AND POTENTIAL RADIATION EXPOSURES IN DIGITAL RADIOLOGY: ANALYSIS OF CUMULATIVE DATA, IMPLICATIONS TO WORKER CLASSIFICATION AND OCCUPATIONAL EXPOSURE MONITORING

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Radiation worker categorization and exposure monitoring are principal functions of occupational radiation safety. The aim of this study was to use the actual occupational exposure data in a large university hospital to estimate the frequency and magnitude of potential exposures in radiology. The additional aim was to propose a revised categorization and exposure monitoring practice based on the potential exposures. The cumulative probability distribution was calculated from the normalized integral of the probability density function fitted to the exposure data. Conformity of the probabilistic model was checked against 16 years of national monitoring data. The estimated probabilities to exceed annual effective dose limits of 1 mSv, 6 mSv and 20 mSv were 1:1000, 1:20 000 and 1:200 000, respectively. Thus, it is very unlikely that the class A categorization limit of 6 mSv could be exceeded, even in interventional procedures, with modern equipment and appropriate working methods. Therefore, all workers in diagnostic and interventional radiology could be systematically categorized into class B. Furthermore, current personal monitoring practice could be replaced by use of active personal dosemeters that offer more effective and flexible means to optimize working methods.

INTRODUCTION

The current radiation protection regulations and guidelines are based on the international standards and recommendations. The fundamental references include ICRP recommendations[(1)] and IAEA Basic Safety Standards[(2)]. European Union published the updated Council Directive (2013/59/Euratom)[(3)] describing the basic safety standards (EU BSS) for ionizing radiation that shall be implemented in each member countries by the February 2018.

Adequate level of radiation safety is set in the Directive, for example, in form of occupational dose limits. However, there is no recognized need any more to average the exposure over the five years period. With respect to new information of the radiosensitivity of the lens of the eye,[(4, 5)] the updated ICRP guidance[(6)] of the dose limit of the lens is also followed in the new EU BSS.[(3)] A technical document was also published by the IAEA about the implications for occupational radiation protection of the new dose limit for the lens of the eye[(7)].

Operational protection of workers is based on prior evaluation to identify the type and magnitude of the occupational exposures, including normal conditions but also possible incidents or potential exposures.

According to the new EU BSS,[(3)] potential exposure means exposure that is not expected with certainty but may result from an event or sequence of events of a probabilistic nature, also including equipment failures and operating errors. However, the EU BSS[(3)] does not give guidance on how this probabilistic nature of the events should be accounted for. The level of preparedness is thus left to the judgement of Member States and implemented in forthcoming national legislation.

Radiation workers are categorized into A and B category, depending on the expected or potential work-related radiation exposure levels. The new EU BSS[(3)] states that those exposed workers who are liable to receive an effective dose >6 mSv per year or an equivalent dose >15 mSv per year for the lens of the eye or >150 mSv per year for skin and extremities, belong to the category A. The EU BSS[(3)] also states that category A workers must be systematically monitored, whereas for category B, the monitoring must be at least sufficient to demonstrate that such workers are correctly classified in the category B. According to the EU BSS,[(3)] the outside workers and visitors must receive the same protection as exposed workers. In practice, the visitors are usually kept out of the X-ray room during the exposure. Therefore, there is typically no need for separate exposure monitoring of visitors at the radiology department.

Occupational exposure monitoring is traditionally implemented with thermoluminescent dosemeters (TLD). However, there has been an increasing interest in using digital active personal dosemeters (APDs) instead of traditional passive dosemeters (TLDs or film badges). Real-time monitoring is a key feature to improve working methods and optimization in radiological procedures as the workers may have immediate feedback on their actions and imaging device settings by an online reading of the APD. The APD technology has developed rapidly during the recent years with regards to functional properties, mechanical tolerance, reliability in pulsed radiation fields and tolerance to environmental interference(8–10). Still, when APDs are used for monitoring of working conditions, the users must be well knowledgeable of the limitations of APDs related to electromagnetic fields and pulsed X-ray fields that are typical in radiology use(8–10).

Assessment of radiation exposures should rely on scientifically established values and relationships. The European Commission describes the technical recommendations for monitoring individuals occupationally exposed to external radiation(11). The dose of radiation workers is measured as personal dose equivalents $H_p(10)$ for deep dose and and $H_p(0.07)$ for shallow dose. In (interventional) radiology the actual connection between the personal dose equivalent recorded by personal dosemeters and the effective dose is not straightforward. The dose measured above the protective lead apron depends strongly upon varying irradiation conditions and placement of the dosemeter. Therefore, the exposure parameters, geometry and shielding conditions must be known accurately to have a reliable estimate of the effective dose based on the personal dosemeter reading. There are several studies investigating the relationship between the dosemeter reading and the effective dose. Siiskonen *et al.*(12) reported that the typical conversion factor of 1/30 from personal dosemeter reading to effective dose overestimates the effective dose in any medical X-ray irradiation settings, especially when thyroid shield is used in addition to lead apron.

The stated conversion factor is based on ICRP 60 organ weighting factors. The latest definition of the effective dose has an updated set of weighting factors.(1) In order to assess the impact of the weighting factors, a sensitivity test was performed based on the calculations presented in Siiskonen *et al.*(12) In particular, the newly identified radiation sensitive organs in the head and neck region and the increased weight of breasts were investigated by increasing the simulated equivalent doses to brain and breasts by a factor of five. As a result, the conversion factor from $H_p(10)$ to effective dose changed <1%. Therefore the conversion factors reported by Siiskonen *et al.*(12) are considered to be valid also with the new organ weighting factors.

The possibility of an unforeseeable incident leading to an unusually large exposure is taken into account in the dose limits for category A radiation workers. For example emergency exposure situations can potentially lead to unusually large exposures. In such situations, the APD technology could provide valuable immediate feedback and lead to more optimal course of action in the context of an overall protection strategy. The ICRP publication 109(13) provides recommendations for the protection of people including the preparedness for, and response to, all radiation emergency exposure situations.

Interventional cardiology procedures and fluoroscopically guided procedures are often associated with high radiation doses. The ICRP publication 120(14) provides guidance for the cardiologist with justification procedures and optimization of protection in cardiology. For clinicians undertaking fluoroscopically guided procedures, the annual dose limit of 20 mSv for the lens of the eye can be exceeded without appropriate radiation protection and training in effective use of the protective devices(15).

The first aim of this study was to analyze the actual occupational exposure data in a large university hospital radiology organization to estimate the frequency and magnitude of potential exposure and, in particular, the probability of unusually large exposures. The second aim was to propose a revised categorization and exposure monitoring practice based on the actual and estimated potential exposures in modern digital radiology.

MATERIALS AND METHODS

The accumulated personal exposure monitoring data from previous study(8) was re-analyzed for this study. The data included five years cumulative personal equivalent dose ($H_p(10)$) of 267 radiation workers including 116 radiologists and 151 radiographers.

The occupational exposure monitoring data was transformed into histogram format for probabilistic modelling. The probability density function was fitted according to the histogram of the occupational exposure data.

The integral of the density function was normalized to produce the cumulative probability distribution (range from 0 to 1.0). Five years cumulative probability was used as an upper estimate for one-year cumulative probability to cover limitations of the original data, for example, the shorter monitoring periods of new workers and unforeseeable incidents. Conformity of the probabilistic model was checked against the annual exposure results spanning 16 years of national monitoring (see Discussion).

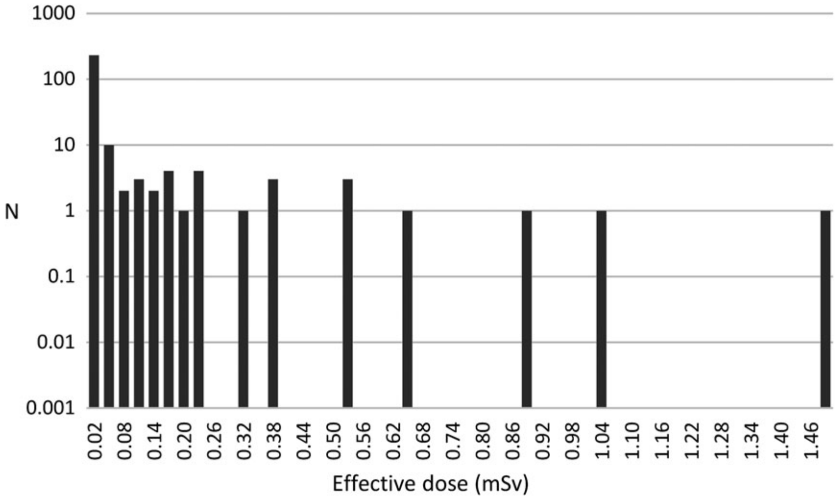

Figure 1. Histogram of the accumulated effective dose values acquired with conservative 1/30 conversion from the personal dosemeter $H_p(10)$ readings from 267 radiation workers (i.e. the effective dose 1 mSv corresponds to 30 mSv dosemeter reading accumulated during the five-year monitoring period).

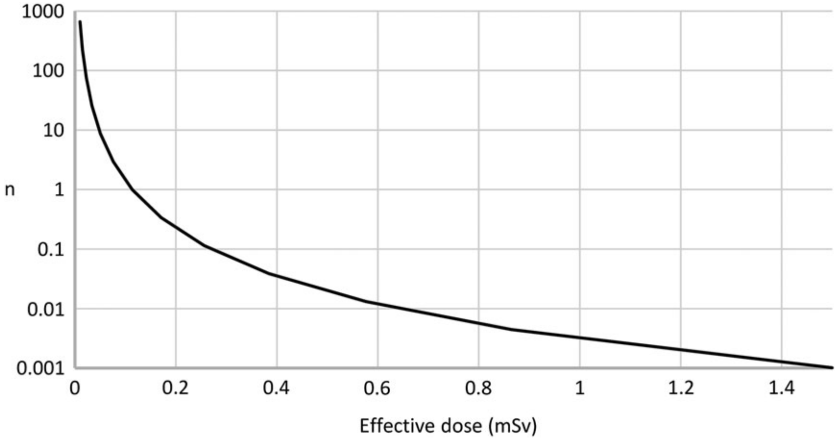

Figure 2. Probability density function fitted to histogram of the accumulated five years of effective dose (reference data is presented in the Figure 1).

RESULTS

The histogram of the occupational exposure monitoring data is presented in Figure 1. The probability density function determined based on the exposure data is plotted in Figure 2.

The equation of the density function was $f(x) = 0.003 \bullet x^{-2.7}$. The cumulative probability distribution calculated from the normalized integral of the density function was applied to certain effective dose levels, as presented in Table 1. Specifically, the probability to exceed annual effective dose limit of 1 mSv was 1:1000, for 6 mSv it was 1:20 000 and for 20 mSv it was 1:200 000.

DISCUSSION

The purpose of this study was to evaluate potential occupational exposure in diagnostic and interventional radiology, based on actual cumulated personal dose monitoring data from 267 monitored workers during five years period in a large university central hospital region. The determined probability density function represents the number of radiation workers exposed to a certain level of accumulated effective dose. This estimated number of exposed worker based on the density function was cross-checked with the actual dose monitoring data to verify the validity of the density function with varying exposure levels. However, it

Table 1. Calculated potential exposure probabilities for accumulated annual effective dose levels from work-related exposure in diagnostic and interventional radiology. Probabilities are based on five years accumulated actual occupational monitoring data used as an overestimate of the exposure during a single year.

Annually acquired effective dose (mSv)	Probability density function (*n*)	Normalized cumulative probability	Probability order of magnitude
0.1	1.4E+00	4.2E-02	1:20
0.5	1.9E-02	2.9E-03	1:300
1	3.0E-03	9.0E-04	1:1000
3	1.6E-04	1.4E-04	1:7000
6	2.5E-05	4.5E-05	1:20 000
10	6.4E-06	1.9E-05	1:50 000
20	1.0E-06	6.0E-06	1:200 000
100	1.4E-08	4.1E-07	1:2 000 000

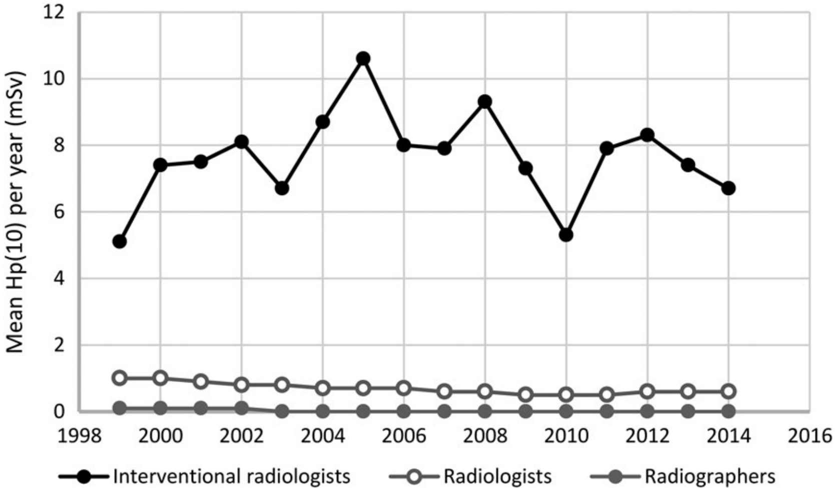

Figure 3. Mean annual $H_p(10)$ doses of radiation workers in radiology during 16 years of monitoring data taken from the national occupational exposure monitoring dose registry.(16) Each year consists roughly of 2000 radiation workers monitoring data. The doses are measured above the protective apron.

should be noticed that the density function extrapolates the higher exposures where there is no data in the actual exposure monitoring. The density function assumes asymptotic behavior where the probability to achieve a certain effective dose approaches zero as the dose level approaches infinity. Specifically, higher exposure incidents—so-called 'black swans'—cannot be fully excluded. However, in parallel with the five years of occupational monitoring data, national authority reports of the nation-wide exposures in radiology were reviewed from 16 years period(16), and are shown in the Figures 3 and 4.

The authority data was in good agreement with the used individual monitoring data of five years and the probabilistic model. For example, the occupational exposure occurrence of 1 mSv effective dose per year for 1:1000 radiation workers in radiology as predicted from the probability model seems to be reasonable in comparison with the maximum annual $H_p(10)$ exposure levels as shown in Figure 4. Considering the 16 years of nationally reported exposure control coverage, notable statistical occurrence of abnormal incidents with increased occupational exposure levels in radiology would have been detected. In particular, the exposures approaching the 6 mSv effective dose per year classification level of class A workers could potentially be seen from the national data consisting effectively more than 30 000 worker years of monitoring data. However, annual effective doses above 1.5 mSv are not seen in the national data. The probability model estimates that 6 mSv effective dose per year could occur once in every cohort of 20 000 workers. Thus, the probabilities given in Table 1 can be taken as upper limits as discussed above. The only reasonable causes for considerably higher occupational exposures would be

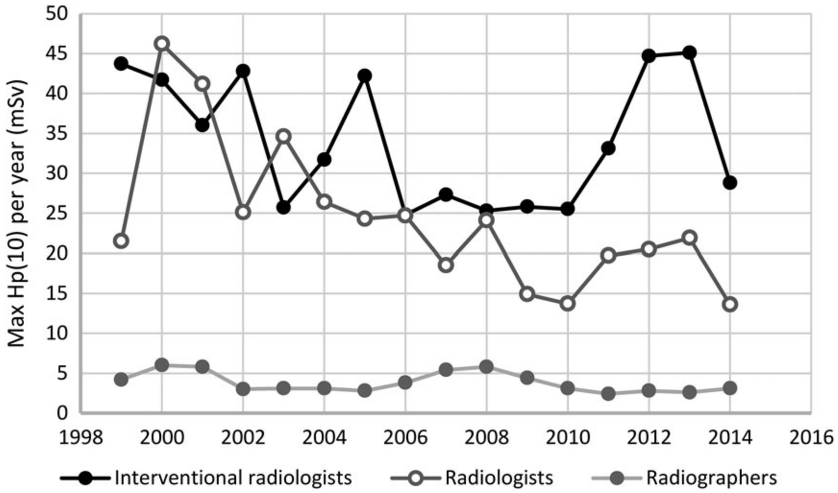

Figure 4. Maximum annual $H_p(10)$ doses of radiation workers in radiology during 16 years of monitoring data taken from the national occupational exposure monitoring dose registry.(16) Each year consists roughly of 2000 radiation workers monitoring data. The doses are measured above the protective apron.

due to negligent and voluntary act. However, such causes should be excluded from the context of occupational exposure evaluation.

A certain limitation of the used five years data raises from the notation that not all of the individually monitored workers accumulated the full five years of monitoring length. However, the effect of these restricted (typically new workers) monitoring periods was estimated to be 25% or less to the overall exposure level. The probability density function used five years of accumulated effective dose that was used as such to provide an upper estimate of the single year of accumulated effective dose. As such, the overestimation of probability density function should well compensate the fairly small bias raising from the restricted exposure monitoring periods and related uncertainties.

Another notation for the results is directed to the studied effective dose parameter in relation to dose limits. There are also equivalent dose limits to radiation workers that must be taken into account when considering radiation safety practices. Especially, the revised limitations to the lens of the eye require special precautions in interventional radiology where local exposures to operator eye region may be a potential risk in prolonged and complicated procedures.

Many international recommendations and codes of practice(7, 11, 14) suggest that the equivalent dose to the lens of the eye in radiology can be estimated from the personal dosemeter reading using $H_p(10)$ as a reference. When the information about the shielding effect of the protective glasses and the ratio of $H_p(10)$ measured at the left side of the chest and the lens dose are combined (see e.g. Martin *et al.*(15)), a relation $H_{eye} = 0.3*H_p(10)$ can be established. It should be noted that uncertainty in this conversion is (at least) several tens of percent. It is assumed here that the protective glasses are always used and that the protective shields reduce the dosemeter reading and the eye dose in the same proportion.

Based on this relation between the measured depth dose and dose to the lens of the eye, the 15 mSv eye lens dose may be exceeded when yearly dosemeter readings approach 50 mSv. Thus, the annual dose limit for the lens of the eye is expected to exceed with a probability of 1:2000 at maximum. However, we note that the eye lens dose may be the limiting factor when the worker categorization is considered.

The optimization of working methods, shielding and technological improvement in digital radiology during the past couple of decades has decreased the occupational exposure remarkably, to the extent that even the mostly exposed interventional radiologists can feel relatively safe. According to the results presented in this study, the actual and potential effective doses of workers in diagnostic and interventional radiology are typically well below the annual exposure level of 1 mSv.

There are strong grounds to revise the present radiation worker categorization and consequently also the dose monitoring practices in radiology. The potential exposure levels of 6 mSv effective dose per year linked to A categorization cannot be considered realistic even in interventional radiology. That would suggest a general B categorization throughout the field of radiology functions and also enable more general use of electric APDs. However, special precautions should be taken with respect to the dose to the lens of the eye. Especially, protective glasses and other shields should be used all the time and they must be properly positioned to effectively block the scattered radiation.

As a practical proposal for the use of electronic active dosemeters, 2–3 dosemeters could be allocated per angiography or interventional radiology suite. One dosemeter would be worn by the physician closest to the source (exposed region and the X-ray beam). Second dosemeter would be worn by the person next closest to the source. Optional third dosemeter could be used as a group dosemeter or in the training use for orientation or further optimization of working methods. Furthermore, one APD could be reserved for each CT fluoroscopy suite.

There are many advantages in the use of active dosemeters. The real-time monitoring enables the immediate observation of abnormal exposure levels and thus also helps to prevent them. Active exposure monitoring avoids observational lag. Thus, the awareness of the exposure level is continuously updated. Due to the sensitivity of active dosemeters, even small exposures can be detected more efficiently. Furthermore, the flexibility of the monitoring allows different exposure scenarios and more targeted exposures (e.g. eye region) to be under surveillance. The active dosemeter systems would be controlled directly by the license holder. Therefore, those systems would require systematic quality control. This would also increase the importance of inspections and audits for overall radiation safety process.

CONCLUSIONS

Occupational exposure data from large university hospital was used to model the frequency and magnitude of potential exposures with further comparison with the national exposure data. Based on the results, it is very unlikely that the A class categorization limit of 6 mSv could be exceeded in diagnostic or interventional radiology, with modern digital radiology technology and appropriate working methods. Therefore, all workers in diagnostic and interventional radiology could be systematically categorized into class B. Furthermore, due to the general B categorization, current personal monitoring practice where conventional dosemeters are worn by all workers could be replaced by a practice where active dosemeters are worn only by a few workers. Active dosemeters could offer more effective and flexible means to improve working methods and optimization in radiology functions.

REFERENCES

1. International Commission on Radiological Protection. *The 2007 Recommendations of the International Commission on Radiological Protection*. ICRP Publication 103. Ann. ICRP **37**(2–4) (Amsterdam, Netherlands: Elsevier) (2007).
2. International Atomic Energy Agency. *IAEA safety standards for protecting people and the environment. Radiation protection and safety of radiation sources: international basic safety standards*. General safety requirements part 3. (Vienna, Austria: IAEA) (2014).
3. Council Directive 2013/59/Euratom. Official J Eur Union 2014; L 013. Available from: ec.europa.eu/energy/sites/ener/files/documents/CELEX-32013L0059-EN-TXT.pdf (Last accessed on August 2015).
4. Shore, R. E., Neriishi, K. and Nakashima, E. *Epidemiological studies of cataract risk at low to moderate radiation doses: (not) seeing is believing*. Radiat. Res. **174**(6), 889–894 (2010).
5. Blakely, E. A. *et al. Radiation cataractogenesis: epidemiology and biology*. Radiat. Res. **173**(5), 709–717 (2010).
6. International Commission on Radiological Protection. *ICRP statement on Tissue reactions / early and late effects of radiation in normal tissues and organs – threshold doses for tissue reactions in a radiation protection context*. ICRP publication 118. Ann. ICRP **41**(1/2) (Elsevier) (2012).
7. International Atomic Energy Agency. *Implications for occupational radiation protection of the new dose limit for the lens of the eye*. IAEA-tecdoc-1731. (Vienna, Austria: IAEA) (2013).
8. Lönnroth, N., Hirvonen-Kari, M., Timonen, M., Savolainen, S. and Kortesniemi, M. *Transition in occupational radiation exposure monitoring methods in diagnostic and interventional radiology*. Radiat. Prot. Dosimetry **151**(1), 58–66 (2012).
9. Clairand, I. *et al. Intercomparison of active personal dosimeters in interventional radiology*. Radiat. Prot. Dosimetry **129**(1–3), 340–345 (2008).
10. Clairand, I. *et al. Active personal dosimeters in interventional radiology: tests in laboratory conditions and in hospitals*. Radiat. Prot. Dosimetry **144**(1–4), 453–458 (2011).
11. European Commission. *Technical Recommendations for monitoring individuals occupationally exposed to external radiation*. Radiation Protection no 160. (European Commission) (Luxembourg) (2009).
12. Siiskonen, T., Tapiovaara, M., Kosunen, A., Lehtinen, M. and Vartiainen, E. *Monte carlo simulations of occupational radiation doses in interventional radiology*. Br. J. Radiol. **80**(954), 460–468 (2007).
13. International Commission on Radiological Protection. *Application of the commission's recommendations for the protection of people in emergency exposure situations*. ICRP Publication 109, Ann. ICRP **39**(1) (Elsevier) (2009).
14. International Commission on Radiological Protection. *Radiological protection in cardiology*. ICRP Publication 120, Ann. ICRP **42**(1) (Elsevier) (2013).
15. Martin, C. J. *Eye lens dosimetry for fluoroscopically guided clinical procedures: practical approaches to protection and dose monitoring*. Radiat. Prot. Dosimetry 1–6 (2015), DOI:10.1093/rpd/ncv431 [Epub ahead of print].
16. STUK – *Radiation and Nuclear Safety Authority, Radiation Practices* – Annual Reports 2000–2015. (Finland: STUK) www.stuk.fi (Last accessed on August 2015).