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OCCUPATIONAL RADIATION EXPOSURE IN FINLAND: EFFECTIVE AND EYE LENS EQUIVALENT DOSES IN HEALTH CARE

Antti Pekkarinen

Doctoral Programme in Materials Research and Nanoscience
Department of Physics
Faculty of Science
University of Helsinki

DOCTORAL DISSERTATION

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Supervising Professor:

Professor Sauli Savolainen

Department of Physics
University of Helsinki, Helsinki, Finland, and
Department of Radiology, HUS Diagnostic Center, Helsinki University Hospital and
University of Helsinki, Helsinki, Finland

Supervisors:

Professor Teemu Siiskonen

Radiation and Nuclear Safety Authority (STUK), and Department of Physics, University of Helsinki, Helsinki, Finland

Docent Mika Kortesniemi

HUS Diagnostic Center, University of Helsinki and Helsinki University Hospital, Helsinki, Finland

Reviewers:

Docent Juha Nikkinen

Department of Oncology and Radiotherapy, Oulu University Hospital, Oulu, Finland

Doctor Mercè Ginjaume

Universitat Politècnica de Catalunya, Barcelona, Catalonia, Spain

Opponent:

Professor Mika Teräs

Institute of Biomedicine
University of Turku
Turku, Finland

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ABSTRACT

Medical workers are regularly occupationally exposed to ionising radiation during, for example, handling of radiopharmaceuticals in nuclear medicine and during x-ray-guided interventional procedures in radiology, cardiology, and surgery. Therefore, medical workers must be sufficiently protected from the harmful effects of the ionising radiation, such as increased cancer risk and radiation-induced eye lens cataract formation. Occupational radiation dose limits set by European Union (EU) and Finnish national regulations are an important method for limiting health risks to personnel. After updated recommendations by the International Commission on Radiation Protection (ICRP) [1–3], International Atomic Energy Agency (IAEA) [4], and European Union Basic Safety Standards [5], the regulatory limit for the equivalent dose to the eye lens was lowered from 150 mSv per year to 50 mSv in a single year and 100 mSv during five consecutive years in the renewed Finnish Radiation Act of 2018 [6], highlighting the need to study the occupational eye doses in Finnish healthcare.

This thesis studied the occupational radiation exposure of Finnish medical workers, including actual and potential effective doses and equivalent doses to the eye lens, and compared them to the regulatory dose limits for radiation workers. Secondly, the proper worker categorization and need for dedicated eye lens dosimeters among medical personnel was assessed, and the possibility of using over-apron $H_p(10)$ for eye lens dose approximation was investigated. Study I estimated the occupational effective doses in medical x-ray use by collecting $H_p(10)$ records from the national dose register and calculating the effective dose distributions for different worker groups from the $H_p(10)$ data. The probabilitites to exceed certain effective dose levels were calculated using statistical modelling in order to estimate potential occupational exposure. In studies II-IV, the equivalent dose to the eye lens was investigated by measuring $H_p(3)$ for different worker groups during clinical practice. The ratio between measured $H_p(3)$ and $H_p(10)$ was calculated to study the possibility of using over-apron $H_p(10)$ to provide an approximation of eye dose. In study IV, $H_p(0.07)$ was also measured and its ratio to $H_p(3)$ was calculated.

The effective dose and eye lens equivalent doses of workers in Finnish diagnostic and interventional x-ray use and nuclear medicine were concluded to be well below the regulatory limits for category A, and for the most part even category B workers, with the exception of the eye lens dose for a very small number of the most exposed interventionalists. $H_p(10)$ measured on the protective equipment was concluded to be sufficient to ensure compliance to

the limits for eye lens equivalent doses as well as effective doses for the majority of workers. Again, an exception to this may be the few most exposed interventional radiologists, who may have eye lens doses nearing the regulatory limits for radiation workers, and thus require optimisation of radiation protection practices and more accurate measurements to estimate the exposure, possibly by dedicated eye dosimeters.

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Kotka, October 2023,
Antti Pekkarinen

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications:

I Pekkarinen A, Siiskonen T, Lehtinen M, Savolainen S, Kortesniemi M. Potential occupational exposures in diagnostic and interventional radiology: statistical modeling based on Finnish national dose registry data. Acta Radiologica. 2019;60(1):68-77.

II Lindholm C, Pekkarinen A, Sipilä O, Manninen A-L, Lehtinen M, Siiskonen T. Estimation of $H_p(3)$ among staff members in two nuclear medicine units in Finland. Radiation Protection Dosimetry, 2020;190(2):176–184.

III Pekkarinen A, Lindholm C, Kortesniemi M, Siiskonen T. Staff eye lens dose in interventional radiology and cardiology in Finland. Physica Medica, 2022;98(11):1-7.

IV Kaasalainen T, Pekkarinen A, Kylänpää L, Rainio M, Tenca A, Jokelainen K, Barner-Rasmussen N, Puustinen L, Udd M, Lindström O. Occupational dose from gastrointestinal endoscopy procedures with special emphasis on eye lens doses in endoscopic retrograde cholangiopancreatography. Endoscopy International Open, 2023;11:E237–E246

The publications are referred to in the text by their Roman numerals.

AUTHOR'S CONTRIBUTION

Study I: The author participated in planning of the study, analysed the dose register data, performed the probabilistic modelling, and wrote most of the manuscript. The author also revised the final version of the manuscript.

Study II: The author analysed the dose register data, performed statistical analysis on the $H_p(3)/H_p(10)$ ratios, and calculated the annual $H_p(3)$ estimates based on the analysis. The author also contributed significantly to the writing and revising of the manuscript.

Study III: The author participated in planning of the study and contributed to the calibration and uncertainty analysis of the eye dosimeters. The author organised the clinical measurements, read the dosimeters, and analysed the measured results. The author also analysed the dose register data and drafted the main body of the manuscript. Additionally, the author revised the final version of the manuscript.

Study IV: The author participated in the planning of the study, organised, and performed the eye lens dosimetry part of the measurements and contributed to the writing of the manuscript.

ABBREVIATIONS

3D	three dimensional
APD	active personal dosimeter
CA	coronary angiography
CBCT	cone beam computed tomography
DSA	digital subtraction angiography
E	effective dose
EU	European Union
ERCP	endoscopic retrograde cholangiopancreatography
H_{eye}	equivalent dose to the lens of the eye
$H_p(0.07)$	personal dose equivalent at a depth of 0.07 mm in the body
$H_p(3)$	personal dose equivalent at a depth of 3 mm in the body
$H_p(10)$	personal dose equivalent at a depth of 10 mm in the body
IAEA	International Atomic Energy Agency
ICRU	International Commission on Radiation Units and Measurements
ICRP	International Commission on Radiological Protection
IC	interventional cardiology
IR	interventional radiology
KAP	kerma-area product
LET	linear energy transfer
LNT	linear-non-threshold
NM	nuclear medicine
PCI	percutaneous coronary intervention
PTA	percutaneous transluminal angioplasty
PET	positron emission tomography
SIRT	selective internal radiation therapy
SPECT	single photon emission computed tomography
STUK	Säteilyturvakeskus (Radiation and Nuclear Safety Authority in Finland)
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

1 INTRODUCTION

Ionising radiation has many useful applications in medicine, and its medical use has been continuously expanding since the discovery of x-rays in 1895. X-rays have long been used for both diagnostic and therapeutic purposes, and this tradition continues in modern diagnostic radiology and external beam radiotherapy, although the latter currently utilises several types of ionising radiation from x-rays to electrons and protons. X-rays are also increasingly applied in image-guided procedures in interventional radiology (IR), interventional cardiology (IC), and different types of surgeries. Ionising radiation is also applied in nuclear medicine (NM), where radiopharmaceuticals are administered to the patient for the purposes of imaging or treatment.

Although extremely beneficial to the patient via improved diagnostics and treatments, the use of ionising radiation carries a risk of adverse health effects, such as cancer or eye lens cataract formation [1,7]. These risks apply not only to the patients, but also to medical workers who are occupationally exposed to ionising radiation during their work. To limit the health risks to acceptable levels, regulatory occupational radiation exposure limits have been implemented [5]. Radiation dose to exposed personnel is measured by personal dosimeters to ensure compliance to these dose limits. Commonly, personnel have been wearing 1-3 dosimeters: 1-2 for effective dose estimation and possibly an additional ring dosimeter for measuring the dose to the hands, depending on the exact role and field of medicine of the worker [7].

Occupational radiation exposure to medical personnel has for long been a topic of considerable research interest. Effective doses to medical radiation workers in different fields of medicine need to be continuously studied, as new diagnostic and treatment methods utilising ionising radiation continue to be developed and implemented. While the newly developed methods benefit the patients, they may increase the occupational exposure of the staff. Determining the magnitude of potential occupational radiation exposure in unexpected situations is an important task, since Article 40 of the European Union (EU) Basic Safety Standards (BSS) [5] demands that potential exposure must be accounted for in categorisation of the radiation workers into categories A and B.

Occupational eye lens doses have been studied widely during the last decade, partly due to the lowered cataract practical threshold dose estimate in the ICRP Publication 118 [1] and the lowered recommended dose limit of 20 mSv per year, averaged over 5 years with no single year exceeding 50 mSv [1]. The lowered threshold dose estimate and limit recommendation have affected the eye lens dose limits in EU-level [5] and Finnish [6] regulations, in which the dose limit for eye lens equivalent dose was lowered from 150 mSv per year to 50 mSv in a single year and 100 mSv during five consecutive years. The lowering of dose limits has raised questions about the need for dedicated eye dosimeters for medical workers, as several studies have reported rather high radiation doses to interventionalists, in some cases exceeding the regulatory limits to radiation workers [8–11]. However, the doses reported by these studies seem very high compared to data from the Finnish national dose register. This discrepancy raises the need to study the matter nationally in Finland.

The general aim of this thesis was to study occupational exposure to Finnish medical personnel in terms of effective dose and eye lens equivalent dose and compare these to the regulatory dose limits for radiation workers. Additional aims were to evaluate the correctness of the categorisation of radiation workers into categories A and B, also accounting for potential exposure, and to assess the need for dedicated eye lens dosimeters among medical personnel.

2 IONISING RADIATION AND ADVERSE HEALTH EFFECTS

Ionising radiation is known to have adverse effects on human health. Perhaps the most well known and most studied is the increased risk of different types of cancer. The increase in cancer risk is currently understood to be due to mutations in the chromosomal DNA caused by radiation damage either indirectly via chemical reactions or directly [3]. The dose-response model associated with the increased cancer risk is currently the linear-non-threshold model (LNT model), meaning that even very low radiation doses contribute to the increased cancer risk, and the risk increases linearly as a function of the dose [3,12]. Although the correctness of the LNT model is debated [13], it is currently the basis of the key principle to optimise the radiation doses occurring to humans to levels as low as reasonably achievable, know as the ALARA principle or optimisation principle [14].

Although likely being the most well-known, the increase in cancer risk is not the only health risk ionising radiation presents. During pregnancy, radiation may cause birth defects or miscarriage of the fetus [3]. Higher doses may cause tissue or organ reactions (also known as deterministic effects) such as circulatory effects, skin irritation, hair loss or even radiation sickness and death. These tissue reactions are associated with threshold doses starting possibly as low as 0.5 Gy for circulatory effects [1] upwards to several grays or more for skin reactions which may only occur during, for example, high dose medical procedures (mostly radiotherapy) to patients. These absorbed doses of several grays are also orders of magnitude higher than the occupational dose limits set for radiation workers. More severe effects such as radiation sickness occur mostly during radiation accidents, which are very rare especially in medicine.

Sufficiently high radiation exposure may also cause radiation-induced cataract formation [1]. Cataract is a vision-impairing clouding of the eye lens. The exact biological mechanism of radiation-induced cataract formation is a topic of ongoing study, and is not perfectly established [1], but has widely been accepted to be related to genomic damage to lens epithelial cells [15]. Like the biological process behind it, the dose response relationship of cataract formation has been studied with increasing activity in the last 15-20 years. Traditionally, it has been understood to be a deterministic effect or tissue reaction with a certain threshold dose below which it does not occur [1]. Currently, the threshold dose estimated by International Commission on Radiation Protection (ICRP) in its recommendations for the purposes of radiation protection is 0.5 Gy [1]. This estimate is defined as the dose resulting in 1% incidence of specified tissue or organ reaction [1]. It serves as a basis for current occupational dose limits set by the EU BSS Directive 2013/59/Euratom [5]. However, uncertainty of the exact threshold dose remains, with some evidence pointing towards lower values than 0.5 Gy or even towards a no-threshold relationship [1,16–18].

3 OCCUPATIONAL RADIATION EXPOSURE AND STAFF RADIATION PROTECTION IN X-RAY-GUIDED INTERVENTIONS AND NUCLEAR MEDICINE

Medical workers are occupationally exposed to ionising radiation during, for example, preparation and administering of radiopharmaceuticals in nuclear medicine or during x-ray guided interventional procedures in radiology, cardiology, and surgical procedures. Although the occupational radiation exposure in medicine can be justitifed (by the ICRP's principle of justification [3]) by the fact that the benefits to the patients from improved care largely outweigh the detriment from radiation exposure, medical workers must be sufficiently protected from the harmful effects of ionising radiation. Since severe radiation accidents affecting medical staff are extremely uncommon in medicine, the potential adverse health effects to non-pregnant medical workers are mostly limited to increased cancer risk and, for the most exposed workers, possibly cataract formation.

Radiation dose monitoring and occupational dose limits are among the most important measures taken to ensure the safety of medical workers, as stated by the ICRP's principle of application of dose limits [3]. The ICRP provides recommendations for radiation protection and exposure monitoring of all radiation workers, including medical personnel and defines the protection quantities to be used in optimisation of radiation use and implementation of regulatory dose limits [7,8]. Currently, the protection quantities are equivalent doses in an organ or tissue, and effective dose. The former is defined as [3]

(1) $$H_T = \sum_R w_R D_{T,R},$$

where w_R are the weighting factors for radiation R and $D_{T,R}$ are the mean absorbed doses from radiation R in the volume of a specified organ or tissue. Effective dose is defined as [3]

(2) $$E = \sum_T w_T H_T,$$

where w_T are the weighting factors for tissue T and H_T are the respective equivalent doses.

The operational quantities currently used in occupational exposure monitoring were defined by the International Commission on Radiation Units and Measurements (ICRU), in the ICRU Report 39 [19] and revised in ICRU report 51 [20]. The quantities currently in use for personal monitoring are called personal dose equivalents $H_p(d)$. Dose equivalent is defined as

(3) $$H = Q\,D,$$

where Q is a quality factor addressing the biological effectiveness of different radiations and D is the absorbed dose evaluated at a specified point. The quality factor Q is a function of the linear energy transfer (LET) of the particles in question in water. The difference between the quality factor Q and the weighting factors w_R is that the former is based solely on LET, whereas the latter are based on relative biological effectiveness of the radiation in question, also including stochastic effects at low doses. However, for photons and electrons, both Q and $w_R = 1$ [3].

In the case of personal dose equivalents, the points the absorbed dose D is evaluated at are specified to be at depths of d under the representative location of the body. For whole-body dose monitoring and effective dose estimation, $d = 10$ mm, for eye lens dose monitoring, $d = 3$ mm and for local skin, 0.07 mm. The respective personal dose equivalent quantities are thus $H_p(10)$, $H_p(3)$, and $H_p(0.07)$. The unit for the personal dose equivalents, as well as for the equivalent doses and effective dose is the sievert (Sv) [19,20].

The international basic safety standards and guidelines for radiation protection are set by the International Atomic Energy Agency (IAEA) [4]. In the EU, basic safety standards in terms of radiation prorection are set by the Council Directive 2013/59/Euratom [5]. Dose limits for occupational exposure are defined in the Euratom directive for effective dose, equivalent doses to skin and extremities and equivalent dose to the lens of the eye. These limits have been implemented in the Finnish national regulations [6,21], and are currently set as shown in Table 1.

Table 1 *Dose limits as specified by Finnish regulations. [a] In addition to the eye lens dose limit of 50 mSv/year, there is an additional limit of 100 mSv for five consecutive years. The dose limits for students and trainees are similar to category B.*

Quantity	Category A limit (mSv/year)	Category B limit (mSv/year)	General population limit (mSv/year)
Effective dose	20	6	1
Eye lens equivalent dose	50 [a]	15	15
Equivalent dose to the skin	500	150	50
Equivalent dose to the hands, arms, ankles, and feet	500	150	-

3.1 CLINICAL PROCEDURES AND RADIATION PROTECTION EQUIPMENT

3.1.1 X-RAY-GUIDED INTERVENTIONAL PROCEDURES: RADIOLOGY, CARDIOLOGY AND GASTROINTESTINAL SURGERY

Radiation exposure to both the patient and staff is affected by the type of x-ray-guided procedure in question. An approximate list of types of x-ray-guided procedures included in studies III-IV is shown in Table 2. All types of procedures performed by the participating interventionalists during the measurement period were included in the study, and the type of each procedure was recorded. A notably large variety of procedures performed can be observed especially for the university hospital interventional radiology unit included in study III.

Table 2 *Types of procedures included in studies III-IV. The list is not exhaustive especially for interventional radiology.*

Interventional radiology	**Interventional cardiology**
Lower limb angiography	Coronary angiography (CA)
Lower limb percutaneous transluminal angioplasty (PTA)	Percutaneous coronary intervention (PCI)
Carotid angiography	Pacemaker implantation
Cerebral artery thrombectomy	Electrophysiological study
Inferior vena cava filter placement	Electrophysiological procedure
Angiomyolipoma embolisation	**Gastrointestinal surgery**
Arteriovenous malformation embolisation	Endoscopic retrograde cholangiopancreatography
Vena spermatica embolisation	Duodenal stenting
Fistula PTA	Anastomotic stricture dilatation
Iliac artery PTA and stenting	Selective internal radiation therapy (SIRT)
Anterior tibial artery PTA	Transarterial chemoembolisation
Popliteal artery PTA and stenting	Lymphography
Superficial femoral artery PTA and stenting	Phlebography
Renal embolisation	Liver angiography

3.1.2 PROTECTIVE EQUIPMENT AND WORKING PRACTICES IN X-RAY-GUIDED INTERVENTIONS

The personal protective equipment worn in x-ray-guided interventions commonly include protective aprons or jacket-skirt combinations and thyroid shields [7,22]. The protective medium has traditionally been lead, but due to its toxicity, non-leaded materials based on e.g. bismuth compounds have been introduced as alternatives to the use of lead in protective clothing [23]. The practice in Finland is to wear a single whole-body dosimeter over the protective clothing at chest height or on the collar. Many Finnish interventionalists also wear protective glasses or visors to protect the radiosensitive eye lenses [22]. The exact design and fit of the protective glasses used vary, resulting in significant variation in the actual dose reduction factors of the glasses in use [24].

As pointed out by ICRP recommendations [7], occupational exposure in interventional procedures is closely related to patient exposure, since the radiation scattered from the patient is the primary source of staff exposure. Therefore, patient dose reduction strategies such as avoiding unnecessary imaging acquisitions (e.g., using a fluoroscopy last-image-hold setting instead of acquiring a single shot image and fluoro loops instead of acquiring a new image series) and the use of optimised imaging protocol settings such as reasonably low pulse rates and dose per frame help to reduce both patient and staff doses [25]. Preferring under-couch x-ray tube irradiation to over-couch or oblique directions when possible and limiting the radiation field to the area of interest using collimators also help to reduce unnecessary scatter radiation towards the personnel [7]. Personnel positioning in the interventional room is crucial in reducing occupational exposure, as the dose rate from scatter radiation decreases rapidly with increasing distance from the patient. Positioning oneself behind a protective shield, behind another staff member or even outside the interventional room are also effective strategies in reducing occupational exposures.

As recommended by the ICRP [7], the interventional suites included in study III were equipped with table-suspended and ceiling-mounted radiation shields. These shields are positioned to protect the staff from radiation scattered from the patient and the patient table, as well as any leakage radiation from the x-ray tube or collimator assembly. The radiation scattered from the patient is considered the largest contributor to staff exposure in most circumstances [7], although tube leakage and collimator scatter may also be significant in some exposure geometries [26]. Radiation protection drapes placed on the patient are also sometimes used to reduce scatter radiation towards the personnel. Movable, rolling, x-ray shields of various heights are commonly utilised to protect the staff.

Finnish interventional procedure rooms themselves usually have at least 3 mm of lead-equivalent structural protection if the room contains a fixed C-arm angiography machine installation [27]. This was also the case for all the IR and IC rooms included in study III. Thus, staff members exiting the procedure room during exposures are completely shielded from any radiation from the

C-arm. In IR procedures, the radiologists, radiographers, and nurses have the possibility of leaving the procedure room during most high-dose cine, digital subtraction angiography (DSA), and 3D cone beam computed tomography (CBCT) acquisitions and are exposed mostly during fluoroscopy. In contrast to this, during IC procedures the cardiologist and assisting staff commonly cannot leave the procedure room during cine acquisitions. In study III, CBCT was used in the IR unit included, but the staff left the procedure room during those acquisitions, as well as during DSA, reducing their exposure. On the other hand, the IC unit did not use CBCT, but the staff stayed in the procedure room during all imaging.

3.1.3 NUCLEAR MEDICINE: PROCEDURES AND RADIONUCLIDES

In nuclear medicine, a large part of the staff radiation exposure usually comes during preparation and administering of radiopharmaceuticals. In the preparation process, activities in the order of several gigabecquerels are commonly handled, and the gamma radiation dose rates on the surface of or near the vials or syringes containing the activity are thus relatively high. The patients who have received a dose of radiopharmaceutical are commonly emitting at least some gamma radiation (or bremsstrahlung, in the case of pure beta emitters such as ^{32}P) to their surroundings. This results in some exposure to the workers during, for example, patient positioning.

A potential source of staff exposures specific to nuclear medicine is accidental radionuclide contamination of clothes, shoes, skin, or even internal contamination, all of which may result in particularly high doses [28]. Personal dosimeters may not be helpful in assessing exposure in these cases of local skin or internal contamination, as the radiation dose distribution is commonly very inhomogenous with dose maximum localised in the specific contaminated part of the body and in the case of beta and alpha emitters, the radiation particles may not penetrate the superficial layers of the dosimeters [29]. For example, in case of internal contamination with ^{131}I, one would seek to measure the gamma radiation emitted by the thyroid to estimate the magnitude of exposure, as iodine is collected in the thyroid [30].

The radionuclides used in the nuclear medicine departments of study II include those commonly used for scintigraphy and single photon emission computed tomography (SPECT) imaging such as ^{99m}Tc, ^{123}I, and ^{111}In. ^{18}F and ^{68}Ga were used for PET imaging and ^{57}Co and ^{68}Ge for quality assurance purposes. Therapy isotopes such as ^{131}I and ^{32}P were also handled in the departments.

3.1.4 PROTECTIVE EQUIPMENT AND WORKING PRACTICES IN NUCLEAR MEDICINE

Protective aprons and thyroid shields similar to those used in radiology are also used in NM in some scenarios. However, for the high photon energy radiation emitted by many common radionuclides, e.g., ^{131}I (364 keV) or ^{18}F, and ^{68}Ga (511 keV), the dose reduction effect of the personal protective equipment is less significant than it is with diagnostic x-ray photon energies of roughly 30-150 keV [31]. Thus, the use of personal radiation protective equipment is less universal than in radiology. This also applies to protective glasses. When personal protective equipment is worn, the whole-body dosimeter is positioned over the protective equipment consistent with the practice when using x-rays in IR/IC.

Thicker lead shielding such as syringe and vial shields are effective in attenuating the higher gamma photon energies and are commonly used. The radiopharmacy cabinets used in preparation of radiopharmaceuticals contain integrated lead shielding to reduce staff exposure during preparation of patient doses. The use of automatic radiopharmaceutical dispencers or injectors in preparation and administration of positron emission tomography (PET) radiopharmaceuticals decreases staff exposure, especially the dose to the hands [32].

Universal radiation protection principles regarding maximising distance and minimising exposure time to radiation sources apply also in nuclear medicine. Keeping as much distance as possible from the radioactive sources and reducing the time of exposure to the radiation help to lower staff doses, as the dose rate is (roughly) inversely proportional to the square of the distance, and the dose is linearly proportional to exposure time. A crucial factor in practical radiation protection in NM is the prevention of staff radionuclide contamination by wearing protective clothing such as gloves, jackets and visors and performing contamination measurements routinely during and after the handling of radiopharmaceuticals [33]. Area monitoring systems with dose rate displays and alarms help in faster detection of radioactive contaminations. Specific hand and shoe contamination detectors also exist, making routine contamination measurements more time efficient.

4 AIMS OF THE STUDY

The general aim of this thesis was to study the occupational radiation exposure of Finnish medical workers, including actual and potential effective doses and equivalent doses to the eye lens, and compare them to the regulatory dose limits. Further, the thesis aimed to assess the proper categorisation of workers into A and B categories and evaluate the need for dedicated eye lens dosimeters among healthcare workers. The aims of the included studies were as follows:

Study I: A retrospective investigation of actual and potential effective doses for medical workers in diagnostic and interventional x-ray use based on national dose register data.

Study II: Investigation of whole-body and eye lens doses to nuclear medicine technicians by measuring the operational quantities $H_p(10)$, $H_p(3)$, and calculating their ratio and correlation. Assessment of the usability of $H_p(10)$ measured over-apron in estimating eye lens doses for nuclear medicine workers.

Study III: Investigation of whole-body and eye lens doses to workers in interventional radiology and cardiology by measuring the operational quantities $H_p(10)$, $H_p(3)$, and calculating their ratio. Assessment of the usability of $H_p(10)$ measured over-apron in estimating eye lens doses for IR and IC workers.

Study IV: Investigation of whole-body and eye lens doses to workers in gastrointestinal surgery, especially endoscopic retrograde cholangiopancreatography (ERCP) by measuring the operational quantities $H_p(10)$, $H_p(3)$ and $H_p(0.07)$.

5 MATERIAL AND METHODS

5.1 COLLECTED DATA AND ESTIMATED QUANTITIES

A summary of collected data and results from each of the studies I-IV is provided in Table 3.

Table 3 *A summary of collected data and type of results from the studies I-IV. KAP stands for kerma-area product displayed by the x-ray equipment.*

Study	Data	Type of results
I	National dose register $H_p(10)$ for category A staff members involved in medical x-ray use	Mean and maximum annual effective dose, probabilities to exceed certain effective dose levels
II	Measured $H_p(10)$, $H_p(3)$, and dose register $H_p(10)$ for nuclear medicine radiographers and nurses	$H_p(3)$, $H_p(10)$, $H_p(3)/H_p(10)$, estimated annual equivalent doses to the eye lens
III	Measured $H_p(10)$, $H_p(3)$, and dose register $H_p(10)$ for staff members in interventional radiology and cardiology	$H_p(3)$, $H_p(10)$, *KAP*, $H_p(3)/H_p(10)$, estimated annual equivalent doses to the eye lens
IV	Measured $H_p(10)$ and $H_p(3)$ for gastrointestinal surgeons and gastroenterologists	$H_p(3)$, $H_p(10)$, $H_p(0.07)$, *KAP*, $H_p(3)/H_p(10)$, $H_p(3)/H_p(0.07)$.

5.2 DATA COLLECTION AND ANALYSIS METHODS

5.2.1 DOSE REGISTER DATA

The national dose registry $H_p(10)$ data utilised in studies I-III was provided by the Radiation and Nuclear Safety Authority of Finland (Säteilyturvakeskus, STUK). The records were obtained by submitting formal data requests to the dose registry. A separate request was sent for each study. The sets of data were anonymized by STUK before being provided to the authors and contained no personal information of workers. In study II, the data could be connected to specific workers in order to facilitate comparison between eye doses measured by eye dosimeters and dose register $H_p(10)$, but the individual data were de-identified and processed in an anonymised format by the authors. In general, the data contained annual $H_p(10)$ records and worker roles, e.g., radiologist, cardiologist, radiographer, or nurse. The data in studies II-III also included five-year cumulative $H_p(10)$.

The initial dataset used in study I covered all Finnish medical x-ray users from 1996 to 2015, a total of 80,761 annual personal $H_p(10)$ entries. From this data, the last ten years (2006-2015) were selected for statistical modelling, totaling 39,364 records. Study II included annual $H_p(10)$ records from years 2009-2018 for all Finnish radiation worker category A nuclear medicine technicians (mostly radiographers and nurses by training, also including some bioanalysts), a total of 2813 individual records. In study III, the data included a total of 3710 individual annual $H_p(10)$ records for interventional physicians from 2016 to 2020. The distribution of dose register data in terms of worker group is shown in Table 4.

Table 4 *Number of collected dose register annual dose records per worker group in each of the studies I-III. For study I, only data from 2006-2015 which were used for statistical modelling of potential exposure probabilities, are shown.*

Worker group	Study I	Study II	Study III
Interventional radiologists	296	0	167
Radiologists	4301	0	1307
Interventional cardiologists	303	0	340
Cardiologists	1627	0	770
Orthopedists	461	0	0
Other interventional physicians	325	0	269
Other physicians	3715	0	857
Radiographers, x-ray use	17761	0	0
Nurses, x-ray use	10575	0	0
Technicians, nuclear medicine	0	2813	0
Total number of annual dose records	**39364**	**2813**	**3710**

In study I, the $H_p(10)$ was converted to effective dose using a conversion factor of 1/30 assuming consistent use of personal radiation protection aprons. This method corresponds to the usual practice of the Finnish national dose registry in the case of x-ray guided procedures. Using this factor should result in a conservative overestimation of the effective dose, especially considering that thyroid shields are commonly used in Finland [34].

5.2.2 STAFF DOSIMETRY

In studies II-IV, $H_p(3)$ was measured by EYE-D (RadCard, Poland) thermoluminescent dosimeters (TLDs) containing MCP-N (LiF:Mg, Cu, P) TLD pellets. The dosimeters were annealed and read by a TOLEDO 654 TLD reader (Vinten Instruments Limited, UK). For each dosimeter reading, $H_p(3)$ was calculated by multiplying the respective TLD reader units with a sensitivity coefficient from calibration measurements. The TLD reader sensitivity, background, and the correctness of the reader settings were routinely checked before reading the dosimeters. Vacuum tweezers were used during the handling of the TLD pellets, which helped to avoid rough mechanical handling or touching the pellets with fingers.

The EYE-D -dosimeters were calibrated with ^{137}Cs for study II and with RQR 7 x-ray quality [35] for studies III-IV using a 20 cm x 20 cm cylindrical water-filled PMMA phantom. The choice of calibration radiation quality was guided by the expected radiation spectra encountered in the clinic: In nuclear medicine, higher energy photons such as the 511 keV annihilation radiation from ^{18}F are expected, whereas in x-ray-guided interventions, one should expect to encounter continuous x-ray scattering spectra with mean photon energies of 40-60 keV [36,37] and maximum photon energies below ca. 120-130 keV, typically less, as the average tube voltage used in e.g. interventional cardiology is in the order of 80 kV [22]. The difference between the scatter spectra and the primary spectra from the x-ray tube depends on the scattering angle and the filtration both by the patient and the x-ray tube and collimator assembly itself. With these factors in mind, radiation qualities with appropriate spectra for the clinical conditions were selected for dosimeter calibration. This resulted in minor differences in $H_p(3)$ relative uncertainty components between studies II and III-IV, as displayed in Table 5. An additional difference in uncertainty estimations between studies II and III-IV was the $H_p(3)$ range (study II: 50 µSv – 10 mSv, studies III-IV: 20 µSv – 5 mSv) included in the dose linearity assessment. In particular, the lower dose point of 20 µSv was included to improve the uncertainty estimation for low doses for studies III-IV, resulting in higher dose linearity uncertainty in those studies, as shown in Table 5.

The eye dosimeters were positioned at the eye level, commonly attached to the arm of personal eyewear, on the most exposed side of the head. In study II, two participants wore the dosimeters attached to a rubber band instead of eyewear. The dosimeters were placed so that the eyewear did not cover the dosimeter from the incident radiation. Therefore, the shielding effect of any protective eyewear is not included in the measured $H_p(3)$. The $H_p(3)$ angular dependency was investigated between angles of 0°-60° and was found to be between 5-7% depending on the radiation quality used, as shown in Table 5.

Whole-body $H_p(10)$ measurements were performed by either TLDs consisting of dosimeter casing and three TLD-100 detectors made of lithium fluoride crystal material (studies II and IV) or (in studies III-IV) by direct ion storage dosimeters (DIS-1, Mirion Technologies, Inc., San Ramon, CA, USA). The TLD-100 were read by the dosimetry service provider (Doseco, Jyväskylä, Finland). The DIS-1 dosimeters were read either by the authors at STUK's dosimetry laboratory (study III) or by the dosimeter users at the clinic with their own, local reader units (study IV) provided by Doseco. In study III, the DIS-1 were factory calibrated, and the calibration was checked by the authors at the dosimetry laboratory. In study IV, the dosimetry service provider was responsible for the calibration and quality assurance of the dosimeters and the reader unit.

The whole-body dosimeters were placed on the protective apron at chest height or on the thyroid collar, depending on where the user usually wears the dosimeter. In the cases where the user was wearing the DIS-1 in addition to their usual TLD, care was taken to position the dosimeters in such a way that they did not block each other.

5.2.3 MEASUREMENT UNCERTAINTY ESTIMATION

$H_p(3)$ measurement uncertainty was assessed by laboratory measurements using a 20 cm x 20 cm (diameter and height) cylindrical water-filled PMMA phantom [38]. Uncertainties were assessed with respect to angular dependency, relative dose response, energy response, reading repeatability, dosimeter batch homogeneity, background reduction, and dosimeter fading. The spectra used in the assessment of energy response were ISO narrow spectra (ISON 25 to 250 [39]), ^{137}Cs and RQR-7. The corresponding relative uncertainties are shown in Table 5.

Table 5 *Components of $H_p(3)$ relative uncertainty (k=1) in studies II-IV. The differences in uncertainties are due to different calibration radiation qualities used. ^{137}Cs was used for study II, whereas the RQR-7 -x-ray quality was used in studies III-IV.*

Uncertainty component	Relative uncertainty, study II (%)	Relative uncertainty, studies III-IV (%)
Repeatibility	2.4	2.4
Batch homogeneity	0.4	0.4
Photon energy	4.9	1.4
Angle	5.0	6.4
Calibration	4.4	4.7
Background reduction	1.3	1.3
Dose linearity	0.6	4.4
Thermoluminescence fading	2.9	2.9

The relative expanded uncertainty $\frac{U}{|y|}$ of the personal dose equivalent quantities was calculated by combining the relative uncertainties $\frac{\Delta x_i}{x_i}$ of all the different relative uncertainty components [40]:

(4) $$\frac{U}{|y|} = k \times \sqrt{\sum_{i=1}^{N}(\frac{u(x_i)}{x_i})^2}$$

A coverage factor of k = 2 was chosen to be used throughout the studies. For study II, the calculation resulted in relative expanded uncertainty for $H_p(3)$ of 18%. For studies III-IV, the corresponding $H_p(3)$ uncertainty was 20%.

For $H_p(10)$ measured with TLD-100, the dosimetry service provider estimated a relative expanded uncertainty (k= 2) of 24%. For DIS-1, the manufacturer reported uncertainties (k = 2) of ±5% for calibration accuracy, ±30% for energy response between 15 keV and 9 MeV, and ±20% for angular response (up to 60° angle at 65 keV). Combining these uncertainties yielded an $H_p(10)$ relative expanded uncertainty of 37% (k = 2) for the DIS-1 $H_p(10)$.

6 RESULTS

6.1 OCCUPATIONAL EFFECTIVE DOSE IN X-RAY-GUIDED PROCEDURES

6.1.1 EFFECTIVE DOSES BASED ON $H_P(10)$ FROM THE NATIONAL DOSE REGISTRY

For an overview of the occupational exposures for workers in medical x-ray use, mean and maximum annual effective doses for years 2006-2015 calculated based on dose registry $H_p(10)$ data for each group of workers are shown in Figures 1-2. The effective dose is estimated by multiplying the $H_p(10)$ readings by 1/30. This factor accounts for the shielding effect of protective aprons, as the $H_p(10)$ is measured over the apron in Finland, and yields a conservative estimate of the effective dose, assuming consistent use of aprons [34].

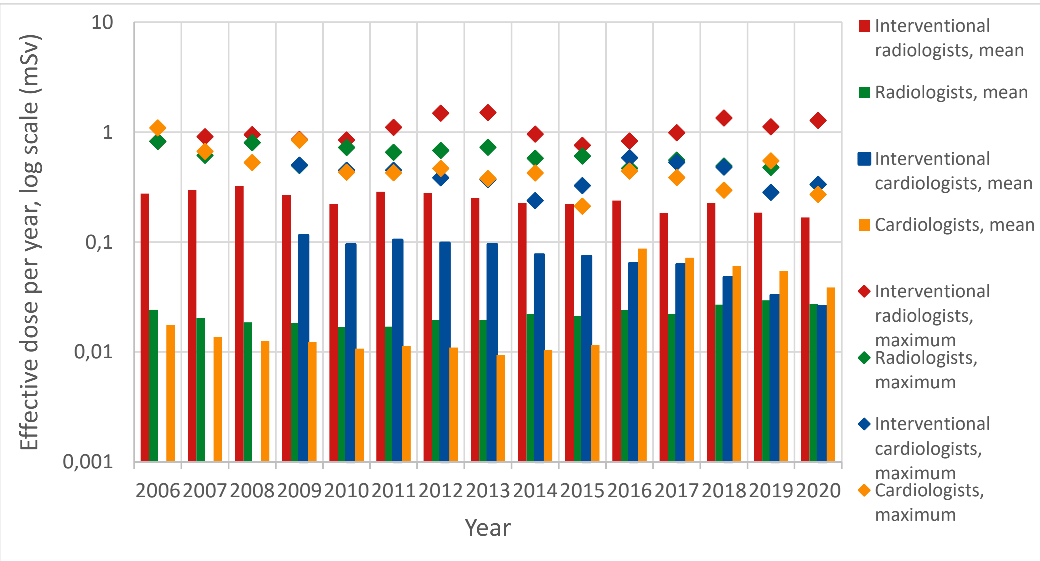

Figure 1 Mean (bars) and maximum (diamonds) effective doses per year for radiologists and cardiologists from the national dose register. Interventional cardiologists exist as a separate group only starting from the year 2009. Note the logarithmic scale of the y-axis.

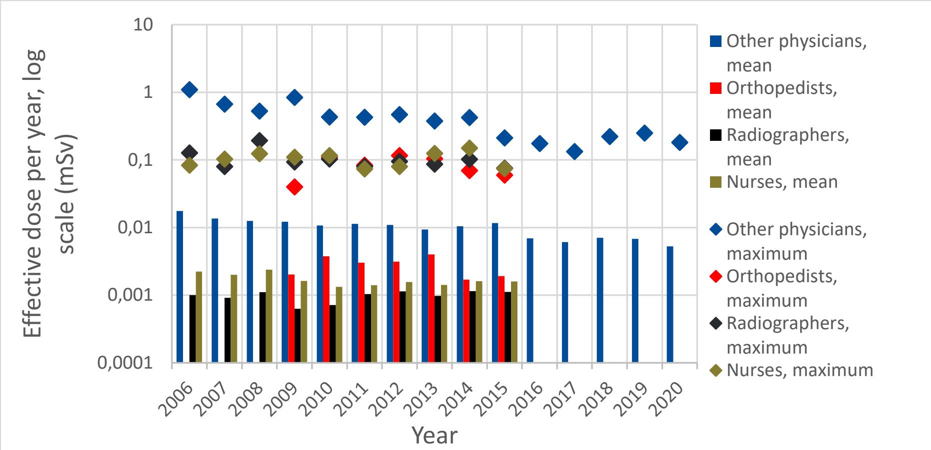

Figure 2 Mean (bars) and maximum (diamonds) effective doses per year for other physicians, orthopedists, radiographers, and nurses from the national dose register. Other physicians include, for example, surgeons and gastroenterologists who perform x-ray-guided procedures. Orthopedists are included in the other physicians' group before 2009, and after that were placed as a separate group in the national dose register. Our data set did not include data for orthopedists, radiographers, and nurses after the year 2015. Note the logarithmic scale of the y-axis.

In addition to the annual mean and maximum values, Table 6 shows the ten highest dose register annual dose records for interventional physicians for the year 2020, the most recent year in our data set. These are displayed to give the reader a picture of the magnitude of the highest annual exposures.

Table 6 *Ten highest dose register annual $H_p(10)$, estimated effective doses (E), estimated $H_p(3)$, and estimated equivalent doses to the lens of the eye (H_{eye}) in the year 2020 for inteventional radiologists and cardiologists. Worker classifications: TR = interventional radiologist, TK = interventional cardiologist. RA = radiologist. In practice, both categories TR and RA include interventional radiologists. Effective dose, $H_p(3)$, and H_{eye} estimates provided here are calculated by multiplying dose register $H_p(10)$ by 1/30, 0.53 and 0.53 · 0.5 = 0.265, respectively. The effective dose estimates assume the use of protective aprons and the H_{eye} estimates assume the use of protective glasses with dose reduction factor of 2.*

$H_p(10)$/year (mSv)	E/year (mSv)	Est. $H_p(3)$/year (mSv)	Est. H_{eye}/year (mSv)	Worker classification
38.4	1.3	20.4	10.2	TR
19.5	0.7	10.3	5.2	TR
15.3	0.5	8.1	4.0	TR
13.1	0.4	6.9	3.5	TR
10.1	0.3	5.3	2.7	TK
10.0	0.3	5.3	2.6	RA
9.7	0.3	5.1	2.6	RA
9.5	0.3	5.0	2.5	RA
9.5	0.3	5.0	2.5	RA
9.3	0.3	4.9	2.5	RA

To facilitate comparison of the results to, for example, the regulatory limit of 100 mSv in five consecutive years for the eye lens equivalent dose, the ten highest dose register five-year cumulative dose records for interventional physicians in 2016-2020 are displayed in Table 7. In tables 6-7, the effective doses are calculated by multiplying the respective $H_p(10)$ by 1/30. The $H_p(3)$ are estimated by multiplying the respective $H_p(10)$ by 0.531, the slope from the linear regression model between over-apron $H_p(10)$ and $H_p(3)$ measured over the protective glasses, shown in Figure 4. The eye lens equivalent dose estimates are calculated by assuming consistent use of protective glasses and a dose reduction factor of 2 for the glasses [24].

Table 7 *Ten highest dose register five-year cumulative $H_p(10)$, estimated effective doses(E), estimated $H_p(3)$, and estimated equivalent doses to the lens of the eye (H_{eye}) in 2016-2020 for interventional radiologists and cardiologists. Worker classifications: TR = interventional radiologist, TK = interventional cardiologist. RA = radiologist. In practice, there is overlap between the categories, e.g. both categories TR and RA include interventional radiologists, even though RA also includes diagnostic radiologists. Effective dose, $H_p(3)$, and H_{eye} estimates provided here are calculated by multiplying dose register $H_p(10)$ by 1/30, 0.53 and 0.53 · 0.5 = 0.265, respectively. The effective dose estimates assume the use of protective aprons and the H_{eye} estimates assume the use of protective glasses with dose reduction factor of 2.*

$H_p(10)$/5 years (mSv)	E/5 years (mSv)	Est. $H_p(3)$/5 years (mSv)	Est. H_{eye}/5 years (mSv)	Worker classification
159	5.3	84	42	TR
91	3.0	48	24	TR
68	2.3	36	18	TR
67	2.2	35	18	TK
62	2.1	33	16	TR
61	2.0	32	16	TR
58	1.9	31	15	RA
52	1.7	28	14	RA
52	1.7	27	14	TR
51	1.7	27	13	TR

6.1.2 POTENTIAL EFFECTIVE DOSES

The probabilities of different groups of workers to exceed effective dose levels of 1 mSv, 6 mSv and 20 mSv (regulatory limits for public exposure, category B and category A workers, respectively) calculated in study I are shown in Table 8.

Table 8 *Probabilities for different worker groups to exceed yearly effective dose levels of 1 mSv, 6 mSv and 20 mSv as predicted by a lognormal fit in the dose register data, years 2006-2015. Only non-zero dose records were used for the distribution fitting.*

Worker group	P (1 mSv)	P (6 mSv)	P (20 mSv)
Interventional radiologists	1:10	1:145	1:1887
Radiologists	1:152	< 1:14 000	< 1:800 000
All cardiologists	1:77	< 1:10 000	< 1:900 000
Orthopedists	< 1:20 000	< $1:10^{8}$	< $1:10^{11}$
Other physicians	1:500	< 1:110 000	< $1:10^{7}$
Radiographers	< $1:10^{7}$	< $1:10^{13}$	< $1:10^{16}$
Nurses	< $1:10^{6}$	< $1:10^{11}$	< $1:10^{15}$
All workers combined	1:175	< 1:12 000	1:500 000

Probabilities to exceed different dose levels were also calculated directly from the dose register data from 2006-2015. No worker exceeded 6 mSv per year in 2006-2015. The only worker groups with instances of yearly effective dose exceeding 1 mSv were interventional radiologists (probability = 1:42) and other physicians (probability = 1: 3333).

6.2 OCCUPATIONAL EYE LENS DOSE

6.2.1 MEASURED OCCUPATIONAL $H_P(3)$ IN NUCLEAR MEDICINE AND X-RAY GUIDED PROCEDURES

Table 9 shows the ranges of measured $H_p(3)$ per procedure as well as extrapolated yearly $H_p(3)$ and ratios $H_p(3)/H_p(10)$ for different worker groups in healthcare. The yearly $H_p(3)$ was estimated by multiplying the $H_p(3)$ measured during the study period with the estimated ratio of working days during the entire year (220 days) to the number of working days in the study period.

Table 9 *Ranges (min - max) for individual workers' $H_p(3)$ per procedure, extrapolated annual $H_p(3)$ and ratios $H_p(3)$ / $H_p(10)$ based on measurements conducted in the substudies. $H_p(3)$ / $H_p(10)$ from linear fit is not available for IR and IC radiographers and nurses, because the data was not linear for these groups.*

Worker group	Number of persons (N)	Number of procedures/time periods (N)	$H_p(3)$ per procedure (range, μSv)	Extrapolated $H_p(3)$ per year (range, μSv)	$H_p(3)/H_p(10)$ (linear fit and range)
Nuclear medicine radiographers and nurses	16	51	n/a	50–3900	0.7 [0.1–2.3]
Interventional radiologists	5	140	7.3–16	1600–7500	0.53 [0.5–0.91]
Interventional cardiologists	5	75	0–23	0–1300	0.53 [0–1.21]
Gastrointestinal surgeons and gastroenterologists	8	604	0–12.5	5–822	0.49 [0.22–2.13]
Interventional radiology radiographers (group dosimeters)	(2)	27	1.04–3.54	320–900	n/a [1.04–3.54]
Interventional cardiology radiographers' and nurse's individual + (group dosimeters)	3 + (2)	177	0.8–3.1	290–900	n/a [0.82–4.08]

6.2.2 POTENTIAL EYE LENS DOSES

The $H_p(3)/H_p(10)$ ratio of 0.53 for interventional radiologists and cardiologists was applied to dose register $H_p(10)$ in order to estimate maximum $H_p(3)$ per year in 2016-2020. Furthermore, a maximum annual eye lens dose estimate was calculated by dividing the maximum $H_p(3)$ per year with a factor of two, representing an estimated dose reduction factor for consistent use of protective glasses as suggested by Magee et al [24]. The results are shown in Figure 3.

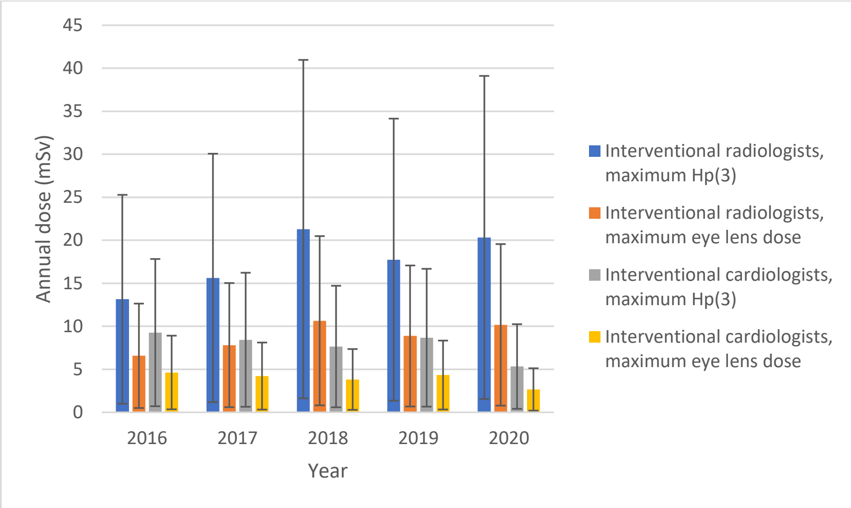

Figure 3 Maximum $H_p(3)$ and eye lens equivalent dose per year for interventional radiologists and cardiologists, years 2016-2020. The $H_p(3)$ values are estimated by multiplying dose register $H_p(10)$ by 0.53, the regression model slope from Figure 4. The eye lens equivalent doses are estimated by dividing the $H_p(3)$ estimates by 2, assuming consistent use of protective glasses. The error bars correspond to an expanded uncertainty with coverage factor $k = 2$, accounting for the measurement uncertainty of $H_p(3)$ and $H_p(10)$ and the linear regression uncertainty, but do not account for the differences in the dose reduction factors of protective glasses.

6.3 RATIO OF MEASURED $H_P(3)$ AND $H_P(10)$

The ratio of $H_p(10)$ measured with common whole-body dosimeter at chest height or on the thyroid collar to the $H_p(3)$ measured next to the eyes outside the protective glasses was investigated for several workers groups in the substudies. For radiographers and nurses, the individual ratios were seen to vary noticeably (0.82-4.08 in interventional cardiology and 1.04-3.54 in interventional radiology). On the other hand, for interventional radiologists, cardiologists, and gastrointestinal surgeons the ratios were mainly below 1. The same behavior of the ratio was observed with nuclear medicine radiographers and nurses, with whom higher doses seemed to correlate with less than unitary $H_p(3)/H_p(10)$ ratios. Illustrations of the relationship between $H_p(3)$ and $H_p(10)$ for different worker groups are provided in Figures 4-6. Figures 4-5 focus on nuclear medicine workers and interventional physicians and provide fitted linear regression models in addition to the data points. Figure 4 shows all the data for interventional radiologists and cardiologists, whereas in Figure 5, data from a single high-dose measurement period (interventional radiologist) is excluded to show the considerable effect of this single data point to the linear fit for interventional radiologists and cardiologists.

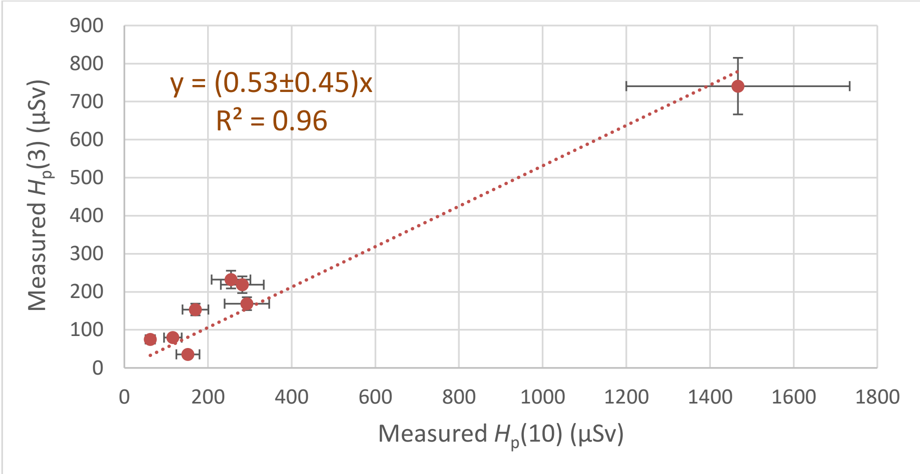

Figure 4 $H_p(3)/H_p(10)$ for interventional radiologists and cardiologists along with linear fits and correlation coefficients. The intercept of the linear fit was set to zero. The ucertainty provided for the slope represents expanded uncertainty with a coverage factor *k* of 2. The error bars represent measurement uncertainties of the doses (*k* = 1). Reprinted with minor modifications from Study III, Figure 2 (License: CC BY 4.0. https://creativecommons.org/licenses/by/4.0/legalcode).

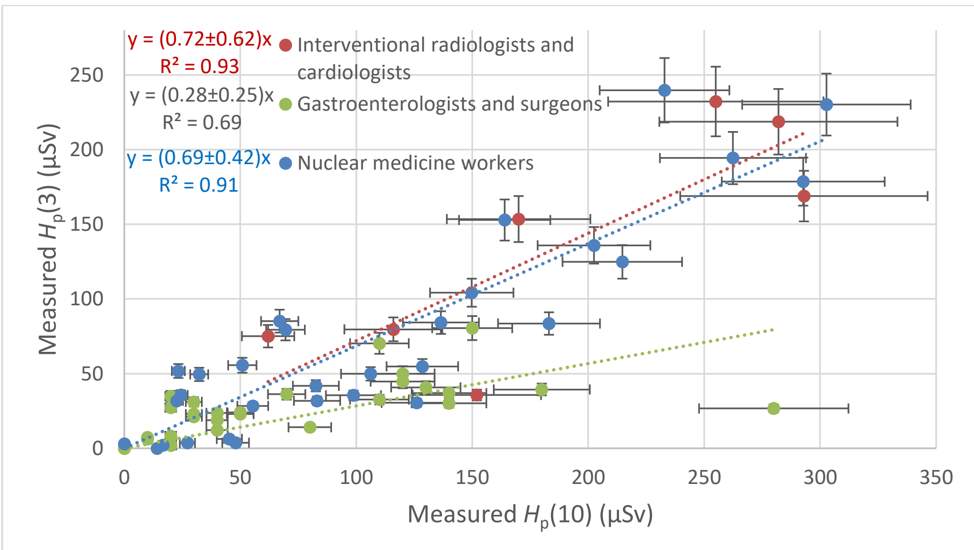

Figure 5 $H_p(10)$ and $H_p(3)$ for different worker groups along with linear fits and correlation coefficients. Blue: Nuclear medicine radiographers and nurses. Orange: interventional radiologists and cardiologists, excluding the worker with the highest dose from Figure 4. Green: Gastroenterologists and gastrosurgeons. The intercepts of the fits were set to zero, which was not done for nuclear medicine workers in study II. The uncertainties for the slopes represent expanded uncertainties (*k* = 2). The error bars represent measurement uncertainties of the doses (*k* = 1).

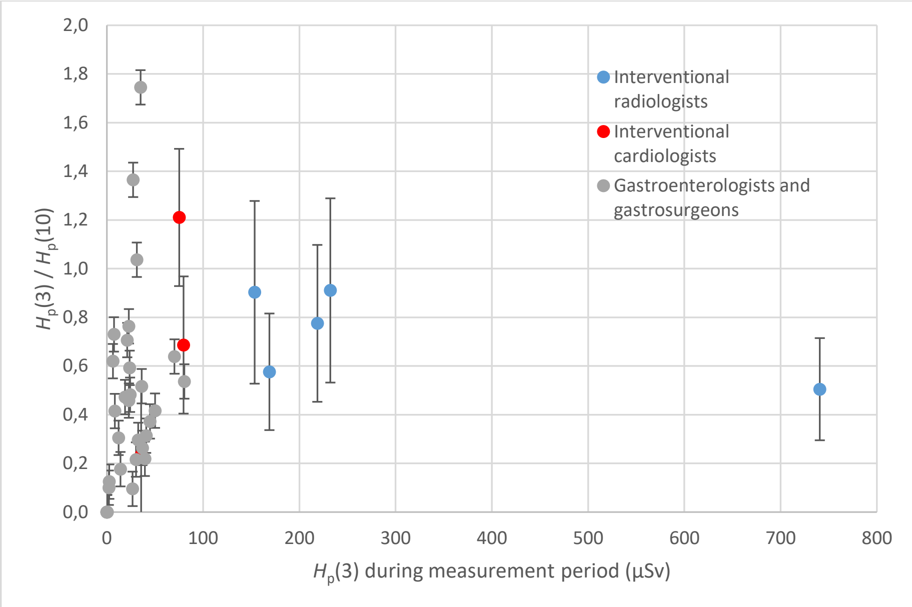

Figure 6 Ratios $H_p(3)/H_p(10)$ for interventional radiologists, cardiologists, and gastrointestinal surgeons/gastroenterologists. Error bars correspond to an expanded uncertainty with coverage factor k = 2.

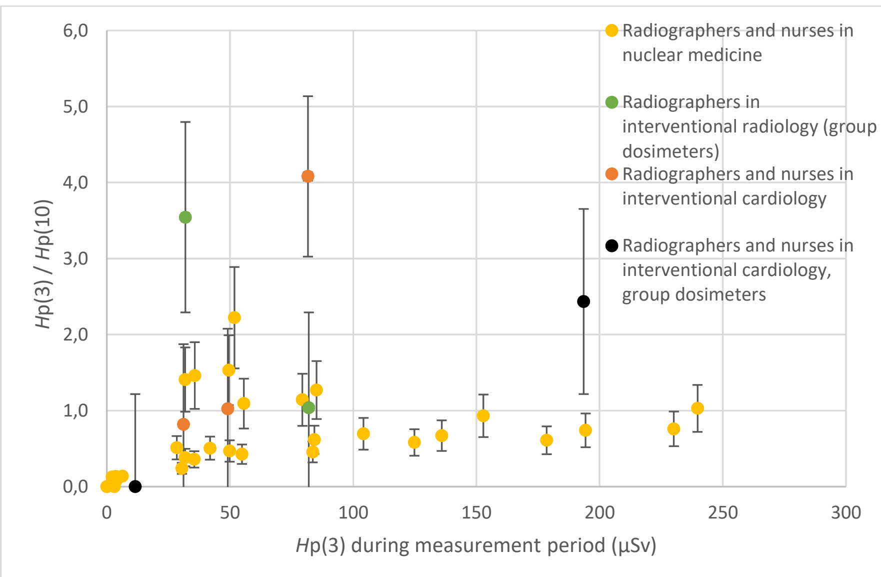

Figure 7 Ratios $H_p(3)/H_p(10)$ for radiographers and nurses working in nuclear medicine interventional radiology, cardiology, and gastrointestinal surgery. Error bars correspond to an expanded uncertainty with coverage factor k = 2.

7 DISCUSSION

7.1 COMPARISON OF THE STUDY RESULTS TO PREVIOUS LITERATURE AND REGULATORY DOSE LIMITS

7.1.1 PREVIOUS STUDIES

The occupational exposure levels measured in this study are low when put in an international context. In terms of $H_p(3)$, the mean $H_p(3)$ per procedure for interventional radiologists in our study III was 10 µSv (range 7.3 µSv-16 µSv). Previous studies on staff eye doses in IR have reported mean doses per procedure ranging from ca. 50 µSv [8,10,43] to 200 µSv [10] depending on the procedures included. For interventional cardiologists, we reported a per-procedure mean of 6.8 µSv (range 0 µSv-23 µSv). Mean per-procedure $H_p(3)$ in previous studies on interventional cardiologists have ranged from 13 µSv to 60 µSv [10,43] per-procedure.

In our study III, $H_p(3)$ for radiographers and nurses in IR and IC were also low (mean 4.2 µSv, range 3.2 µSv-4.8 µSv and mean 1.9 µSv, range 0.82 µSv-3.1 µSv, respectively) compared to the 11 µSv-24 µSv reported by e.g. Principi et al. [42] in their study for IC nurses. The same trend continues in study IV and ERCP procedures, with median $H_p(3)$ per procedure of 0.6 µSv and 0.4 µSv for gastroenterologists/gastrosurgeons and assisting staff, respectively. For instance, in the ORAMED study [10], the median eye lens dose for surgeons in ERCP was reported to be 18 µSv per procedure. In study II, we report an annual $H_p(3)$ mean of (1.1 ± 0.1) mSv and a range of 0.05 mSv - 3.9 mSv per year for nuclear medicine technicians, mostly radiographers and nurses by training. This is lower than the range 0.6 mSv – 9.3 mSv reported by Dabin et al. [43], as well as below the 8 mSv and 4.5 mSv reported by two previous studies [44, 45]. A summary of the $H_p(3)$ results compared to previous studies is shown in Table 10.

Table 10 *A comparison of $H_p(3)$ per procedure, extrapolated annual $H_p(3)$ and ratios $H_p(3)$ / $H_p(10)$ from studies II-IV to some of the published literature. The staff included are interventional physicians unless noted otherwise. Reprinted from Study III, Table 2 with modifications (License: CC BY 4.0. https://creativecommons.org/licenses/by/4.0/legalcode).*

Publication	Worker group/procedure type	$H_p(3)$ per procedure (μSv)	Extrapolated Hp(3) per year (μSv)	$H_p(3)$/Hp(10)
Study II	Nuclear medicine radiographers and nurses	n/a	50 - 3900	0.7 [0.1 - 2.3]
Study III	Interventional radiologists	10 (mean) 7.3 - 16 (range)	1600 - 7500	0.53 [0.5 - 0.91]
Study III	Interventional cardiologists	6.8 (mean) 0 - 23 (range)	0 - 1300	0.53 [0 - 1.21]
Study III	Interventional radiology radiographers (group dosimeters)	1.04 - 3.54 (range)	320 - 900	n/a [1.04 - 3.54]
Study III	Interventional cardiology radiographers and nurses (individual + group dosimeters)	0.8 - 3.1 (range)	290 - 900	n/a [0.82 - 4.08]
Study IV	Gastrointestinal surgeons and gastroenterologists	0.6 (median) 0 - 12.5 (range)	5 - 822	0.49 [0.22 - 2.13]
Study IV	Gastrosurgery assisting staff (group dosimeters)	0.4 (median) 0 - 12.2 (range)	500	n/a
Efstathopoulos et al. 2011 [41]	Mixed IR	47 (mean) 0-557 (range)	n/a	n/a
Efstathopoulos et al. 2011 [41]	Mixed IC	13 (mean) 0-61 (range)	n/a	n/a
Vanhavere et al. 2011 (ORAMED) [10]	Carotid & brain angiography/angioplasty	ca. 50 (mean)	n/a	n/a
Vanhavere et al. 2011 (ORAMED) [10]	Embolisations	ca. 200 (mean)	n/a	n/a
Vanhavere et al. 2011 (ORAMED) [10]	Lower limb angiography/angioplasty	ca. 50 (mean)	n/a	n/a

Vanhavere et al. 2011 (ORAMED) [10]	Renal angiography/angioplasty	ca. 50 (mean)	n/a	n/a
Vanhavere et al. 2011 (ORAMED) [10]	CA/PCI	ca. 50 (mean)	n/a	n/a
Vanhavere et al. 2011 (ORAMED) [10]	Radiofrequency ablation	ca. 40 (mean)	n/a	n/a
Vanhavere et al. 2011 (ORAMED) [10]	Pacemaker/implantable cardioverter defibrillator implantation	ca. 50-60 (mean)	n/a	n/a
Kopec et al. 2011 [46]	Nuclear medicine staff	n/a	n/a	0.7 - 1.1
Leide-Svegborn 2012 [44]	Nuclear medicine staff	n/a	8000	n/a
Summers et al. 2012 [45]	Nuclear medicine staff	n/a	4500	n/a
Jacob et al. 2013 [11]	Cerebral angiography	25 (mean)	n/a	n/a
Struelens et al. 2013 [47]	Interventional radiologists and neurosurgeons, vertebroplasty and kyphoplasty	34 (median), 836 (maximum)	n/a	n/a
O'Connor et al. 2015 [8]	Mixed IR	55 (mean) 16.5 - 143.2 (range)	n/a	n/a
Principi et al. 2015 [42]	Mixed IC, physicians	42-251 (range)	n/a	n/a
Principi et al. 2015 [42]	Mixed IC, nurses	11-24 (range)	n/a	n/a
Dabin et al. 2016 [43]	Nuclear medicine staff	n/a	600 - 9300	0.3 - 2.3
Aarsnes et al. 2018 [48]	Transcatheter aortic valve implantation	50-60 (median)	n/a	n/a
Tanaka et al. 2019 [49]	Mixed IR, physicians	n/a	18 600	0.3 – 0.7
Morcillo et al. 2021 [50]	Mixed pediatric and adult IR	70 - 180 (range)	n/a	n/a

The general picture is rather similar in terms of effective dose. The mean annual effective doses calculated for Finnish interventional radiologists from the national dose register data in study I (as displayed in Figure 1) are approximately 1/10 of the typical range of 2-4 mSv mentioned in ICRP report 139 [7]. Even the highest annual effective doses in Finland are only in the order of 1.5 mSv, falling in the lower end of the range for typical doses. For another example, Chida et al. [51] reported annual mean effective doses of 3.00, 1.34 and 0.60 mSv for interventional radiologists, IR nurses and IR radiologic technologists, respectively. For interventional radiologists, the mean effective dose reported by Chida et al. is approximately ten times higher than mean effective doses calculated based on Finnish dose register data, and in fact even higher than the maximum annual effective dose for interventional radiologists in years 2006-2015 in Finland, as shown in Figure 1. The maximum annual effective doses for Finnish radiographers and nurses are in the order of 0.1 mSv, as shown in Figure 2, much lower than the 0.60 mSv mean value reported by Chida et al. In a 2020 study on occupational exposure in radiology and cardiology in the United Arab Emirates, the mean annual effective dose per worker was found to be 0.38 mSv – 0.62 mSv, notably higher than our results from study I [52]. The maximum effective dose reported by Elshami et al. was 8.63 mSv, almost six times the maxima reported in study I for Finland in 2006-2015 [52]. Finally, the 2008 Report by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [53] reports average annual effective doses for workers in diagnostic and interventional radiology. The averages for all monitored workers in 2000-2002 range from 0.07 mSv (conventional radiology, Denmark) to 3.97 mSv (interventional cardiology, Greece) per year. However, the UNSCEAR report data should be interpreted with caution, as the dose values reported for e.g. Finland seem to be over-apron $H_p(10)$ misidentified as effective doses, with the 2000-2002 Finnish averages for conventional and interventional radiology stated as 0.22 mSv and 4.95 mSv, respectively.

7.1.2 REGULATORY DOSE LIMITS AND WORKER CATEGORIZATION

In terms of estimated effective dose in medical use of x-rays, while covering both actual and potential exposures, the dose limit of 20 mSv per year for category A workers was not exceeded by any staff member included in this thesis. Not even the category B limit of 6 mSv per year was exceeded, suggesting that in terms of effective dose, most workers in medical x-ray use could be placed in category B in Finland. For these workers, the limiting quantity seems to be the equivalent dose to the lens of the eye.

The annual eye lens equivalent doses estimated in the studies of this thesis are mostly clearly below the dose limits for radiation workers, and even below the category B limit of 15 mSv per year. Exceptions to this are some interventional radiologists as shown by the dose register data analysis in, e.g., Figure 3. For the few most exposed interventional radiologists, the maximum estimated eye lens equivalent doses may exceed 20 mSv per year, which may potentially result in exceeding the eye lens dose limit of 100 mSv per five consecutive years. The potential for high eye lens doses certainly places those interventional radiologists and cardiologists who perform large numbers of x-ray guided procedures into radiation worker category A. On the other hand, radiographers and nurses in IR and IC could possibly be moved to category B in terms of effective and eye lens dose, even considering potential exposure. The doses measured for nuclear medicine technicians in study II suggests that some of them could also be placed into category B, but the potential exposure due to skin or internal contamination is likely to necessitate maintaining their current categorisation into category A. The magnitude of potential exposure from contamination incidents and the likelihood of accidental contamination for Finnish nuclear medicine workers should be investigated further. Lastly, it must be noted that our study did not cover radiotherapy workers, who could potentially be exposed to radiation especially during accidents. Their potential exposure could be an interesting topic for future studies.

Based on the results of this study, a vast majority of the Finnish medical radiation workers in diagnostic and interventional x-ray use and nuclear medicine could be categorised into category B in terms of effective dose and equivalent dose to the eye lens. In fact, most workers currently in category A are unlikely to even exceed the dose limits (1 mSv/year for effective dose and 15 mSv/year for the eye lens equivalent dose [5,21]) for the general population. However, some interventional radiologists may need more rigorous eye lens dose monitoring and optimisation on radiation protection to lower their occupational exposure.

7.2 SOURCES OF UNCERTAINTY

Every step of the occupational radiation dosimetry workflow has an uncertainty contribution towards the combined uncertainty of the final results, i.e., the estimated effective dose and equivalent doses. From technical factors such as dosimeter design and calibration to practical factors such as staff compliance to the use of dosimeters, each uncertainty factor must be accounted for in the uncertainty budget. Even if the dosimeter readings themselves were perfectly accurate, the conversion from the measured operational quantities to protection quantities represents a source of uncertainty.

Any dosimeter system has technical measurement uncertainties dependent on dosimeter design and calibration. These uncertainty factors include the radiation energy spectrum, incident radiation angle and radiation dose. The technical uncertainties can be accurately assessed by measurements in the calibration laboratory, as was done in this study for the EYE-D -dosimeters. Communication of the dosimetric uncertainty from the calibration laboratory to dosimetry service and onwards to the radiation protection experts of the user organisation is important since protection of the workers is the undertaking organisation's responsibility, as highlighted by the EU BSS [5] and national regulations [6].

The consistency of dosimeter use also presents a source of uncertainty: if left unused, even the best dosimeters do not provide accurate estimates of staff exposure to the radiation protection officers and national authorities. In an international survey conducted by the IAEA, only 76% of interventional cardiologists reported that they always wear their personal dosimeter during interventions [54]. This non-ideal compliance to dosimetry practices also represents a source of uncertainty related to dose register data. When very low doses are considered, another source of uncertainty is the effect of the dose recording threshold. Currently in Finland, measured $H_p(10)$ below 0.1 mSv and $H_p(0.07)$ below 1 mSv are marked as zero in the dose register, which must be accounted for in data analysis.

The estimations of effective dose based on measured $H_p(10)$ and eye lens equivalent dose from $H_p(3)$, respectively, contain significant uncertainty. The over-apron $H_p(10)$ to effective dose conversion factor of 1/30 used in study 1 is a conservative estimate when protective aprons or protective jackets and skirts are used consistently [34]. Fortunately, their use is rather universal in both Finnish [22] and international [54] interventional and operating rooms and thus unlikely to present a significant error factor in the results. On the other hand, thyroid shields are also commonly used [22], likely resulting in an overestimation of the real effective dose by the 1/30 conversion factor, with the factor of 1/60 being more appropriate [34]. Accounting for the use of both aprons and thyroid shields, Siiskonen et al. reported that the over-apron dosimeter reading overesti mated the effective dose by an average factor of 130 in a Monte Carlo simulation study [34]. Other Monte Carlo or phantom studies on the conversion factor between effective dose and over-apron $H_p(10)$ have reported factors in the range of 0.011 – 0.18 depending on tube potential, lead equivalence of the protective apron, and use of thyroid protection [58]. In practice, differences in thickness, material and fit of the personal protective equipment will always result in some variation in their dose reduction factors. For this reason, a sensitivity analysis was performed in Study I to investigate the effect of the conversion factor (range: 1/10 – 1/60) to the probabilities of exceeding different effective dose levels, and it was noted that even with a factors as high as 1/10, the conclusions of the study would not have been affected. The use of double dosimetry, in which one dosimeter is placed over the protective apron and one underneath it, would likely reduce the uncertainty related to effective dose estimation. However, based on the low effective doses reported in study I, such practice is not warranted in Finnish radiology, since exceeding the effective dose limit for category A workers is very unlikely.

In studies III-IV $H_p(3)$ was measured outside the protective glasses, which commonly reduce the dose by at least a factor of two [24]. The exact dose reduction factor depends on the type of glasses or visor worn [24,55] and may be much higher than 2. For example, D'Alessio et al. [55] report reduction factors of 6.8 and 9.1 for a full-face visor in two measurement geometries. The exact position of the dosimeter also matters, causing variation to the ratio between measured $H_p(3)$ and real equivalent dose to the eye lens. The ratios were reported to range from 0.2 to 1.6 by da Silva et al [56]. The lowest ratios were found when measuring $H_p(3)$ under the glasses, considerably underestimating the real eye lens equivalent dose.

In the estimation of potential occupational exposures in nuclear medicine, contamination by radioactive substances must be accounted for. The usability of personal dosimeter readings may be limited in case of local skin or internal contamination, especially with radionuclides emitting beta or alpha radiation [29]. This also includes any dedicated eye dosimeter. For example, in the case of skin or eye contamination with, e.g., ^{32}P or even ^{18}F, the local dose in the contaminated area may be very high with the personal dosimeters not registering much lower doses [29]. This highlights the importance of avoiding personnel contamination by using appropriate protective equipment and performing contamination measurements routinely.

7.3 DOSIMETRY CONSIDERATIONS

7.3.1 USE OF $H_P(10)$ AND RATIOS $H_P(3)/H_P(10)$ TO ESTIMATE EYE LENS DOSES

The ratio of eye dosimeter $H_p(3)$ to whole-body dosimeter $H_p(10)$ is affected by the exact location and model of the respective dosimeters. In study IV, it was noticed that $H_p(10)$ and $H_p(0.07)$ readings from DIS-1 dosimeters were systematically lower than those from TLDs worn simultaneously. This may be due to differences in energy response curves of the respective dosimeters when measuring low-energy x-rays used in C-arm guided gastrointestinal surgery. Although the differences were mostly within the expanded uncertainties (k = 2) reported by the dosimetry services, the matter should be investigated further. In general, awareness of the uncertainties associated with measuring different types of radiation with different models of personal dosimeters should be improved among radiation protection officers and dosimeter users. The usage, positioning, and model of protective devices, e.g., ceiling-mounted protective glass shields to protect the head and upper body. These factors inevitably cause variations to the $H_p(3)/H_p(10)$, making the eye lens dose estimation from over-apron $H_p(10)$ less accurate. Even the differences in operators' heights cause some variation in the ratio of the two quantities [49]. However, the ratio between eye dosimeter and whole-body dosimeter reading for interventional physicians has been shown to be below or equal to one in several previous studies [49,57,58], lending futher credibility for the use of whole-body dosimeter over-apron $H_p(10)$ as a conservative estimate for eye lens dose.

The ratio of $H_p(3)$ to $H_p(10)$ was calculated in this study for several groups of healthcare workers. For the most exposed interventional radiologists and cardiologists, the two quantities were linearly correlated (R^2 =0.92-0.97), as shown in Figures 4-5. The variations in ratios to $H_p(3)$ to $H_p(10)$ were at their largest for radiographers and nurses in x-ray guided interventions, with $H_p(3)/H_p(10)$ ranging between 0.82 – 4.08. This is opposite to what was reported by Principi et al. [42] in a previous study for interventional cardiology staff, where $H_p(0.07)$ measured on the protective equipment correlated well with $H_p(3)$ for nurses, but not for interventionalists. The different dose quantities used may affect the results to a degree but are unlikely to be the full explanation to the differences in correlation between the studies. On the other hand, good linear correlation between $H_p(3)$ and $H_p(10)$ was observed for nuclear medicine technicians in Study II. The $H_p(3)$ to $H_p(10)$ ratio from linear regression analysis of 0.7 in Study II is supported by the previous study of Kopeć et al, where $H_p(3)/H_p(10)$ between 0.7-1.1 were reported [59]. Dabin et al. reported a wider range of 0.3-2.3 but still a clear correlation between $H_p(3)$ and $H_p(10)$, although the correlation was poorly linear.

In our study, the variation of $H_p(3)/H_p(10)$ for the personnel assisting in x-ray-guided interventions might be explained by the very low exposure of radiographes and nurses, who are usually able to position themselves from a further distance away from the patient than interventional physicians, resulting in lower radiation exposure among assisting staff, nearing the limits of the dosimeter system's sensitivity. Indeed, the measured $H_p(3)$ for IR and IC radiographers and nurses were low enough to conclude that even the 15 mSv per year limit for category B workers' eye lens dose will not be exceeded for these workers. This is strongly supported by low $H_p(10)$ levels on the national scale shown by the dose register data for radiographers and nurses in medical x-ray use, displayed in Figure 2. Thus, despite the variation in the ratios $H_p(3)$ to $H_p(10)$, dedicated eye dosimeters are not required for the majority of workers to ensure compliance to eye lens dose limits.

7.4 FUTURE POSSIBILITIES

ICRP publication 147 [60] concluded that while the effective dose may be considered as an approximate indicator of the increase in stochastic risk caused by radiation, estimates of individual risk should use organ or tissue doses and more specific dose risk models. Additionally, the ICRP recommends the use of absorbed dose over equivalent dose for setting dose limits to avoid tissue reactions. These recommendations are likely to result in changes to protection quantities used in future legislation, as well as encourage improvements on individual radiation risk estimation practices. New information on biomechanisms of radiation-induced cataract formation and its threshold dose may affect protection practices. In particular, if the threshold dose for cataract formation was found to be much lower than the current 0.5 Gy estimate (or even zero), current dose limits and protection practices would not be adequate and would need to be revised [1].

ICRU report 95 [61] introduced a system of new operational quantities to replace, among others, the personal dose equivalent quantities currently in use. The new quantities will, in time, result in changes in dosimeter design and calibration, as well as changes in the quantities stored in the national dose register. Adoption of new dosimetry technologies may also transform the field of occupational dosimetry. In addition to TLDs, different occupational dosimeter technologies are increasingly available also to medical users. Dosimeters based on direct ion storage technology can be easily read by the user at any time without losing the dose information, allowing for more convenient measurements of staff doses per procedure and optimisation of staff exposure in different situations. Furthermore, active personal dosimeters (APDs) displaying dose reading and dose rate in real time are becoming more common. Providing immediate feedback for the user, APDs can be very useful for optimisation and training purposes.

Estimates of occupational radiation exposure may also be calculated without the worker wearing any dosimeter at all by calculation models based on Monte Carlo simulations or different statistical or machine learning methods. These calculations typically require multiparametric input data, for example reference point air kerma or air-kerma dose product from the imaging system, irradiation geometry and personnel location information in the operation room. The PODIUM project [62] aims to estimate occupational exposure by utilising Monte Carlo simulations and online location tracking systems. Additionally, two software tools based on Monte Carlo simulation results have already been published for interventional cardiologists' eye lens dose estimation, and are freely available for use [63]. Another potential field of development in calculation models lies in artificial intelligence. Machine learning methods can be utilised to process multiparametric data and could potentially be trained to generate predictions of occupational exposure in different situations.

Use of ionising radiation in surgery is a growing field of medical occupational dosimetry. Hybrid operation rooms, in which planar angiography and even 3D CBCT acquisitions can be performed, are rapidly becoming common. While the possibility of high-quality imaging and the option to perform endovascular procedures in the operating theatre benefits the patients overall via better treatment results, it can potentially increase the occupational radiation exposure to surgical staff [25]. Sufficient resources for personal dosimetry and focus on optimising the use of radiation in the hybrid operation rooms are important in ensuring that the radiation risks for workers in surgery remain on acceptable levels.

Occupational equivalent doses to the skin and extremities are routinely measured in nuclear medicine by using ring dosimeters, but not commonly monitored in x-ray guided interventions. Although studies have investigated these quantities also in interventional practice, their measurement and comparison to dose limits (or alternatively, estimations of local absorbed doses) in different x-ray-guided procedures present possible topics for future studies.

8 CONCLUSIONS

In terms of effective dose and equivalent dose to the eye lens, the exposure of workers in Finnish diagnostic and interventional x-ray use and nuclear medicine to ionising radiation is mostly well below the regulatory occupational limits for radiation workers. The only exception to this rule may be the eye lens dose for a very small number of the most exposed interventional radiologists. The most exposed interventionalists should wear suitable protective glasses, utilise ceiling-mounted radiation shields and optimise their working methods as well as reasonably possible. Optimising imaging protocols and favoring low-dose parameters for default fluoroscopy and exposure settings are important, as these measures reduce the dose to both the patient and the staff. Leaving the procedure room during DSA and 3D acquisitions should be standard practice whenever possible without compromising patient care.

Most workers in Finnish healthcare are exposed not only below the category A limits, but also below those for category B or even for the general population. As shown by the low probabilities for high exposures from our study I, many category A workers could safely be placed in category B, even when accounting for the potential exposure. Although exposure levels must be monitored by the necessary number of group dosimeters to ensure the correct categorisation of workers, re-categorisation of workers could reduce the number of individual dosimeters for virtually non-exposed personnel. The increased use of group dosimeters would also have the advantage of accumulating higher dose per dosimeter, as currently many individual monthly dose readings are minimal, even below the sensitivity of the dosimeter system.

Whole-body dosimeter $H_p(10)$ measured over the protective equipment gave a conservative overestimate of the eye dosimeter $H_p(3)$ for the most exposed worker groups included in our study: interventional radiologists, cardiologists, gastrointestinal surgeons, and nuclear medicine workers. For radiographers and nurses in x-ray use, there was considerable variation in the ratios between measured $H_p(10)$ and $H_p(3)$, strongly suggesting that the whole-body dosimeter reading is less accurate as an indicator of eye lens dose for these workers. However, radiation exposure for these groups was relatively low, much lower than category A or B regulatory limits for eye lens dose.

Therefore, it is concluded that despite the variation in ratios of $H_p(3)$ and $H_p(10)$, the $H_p(10)$ measurements by whole-body dosimeters provide a sufficient method for ensuring the compliance to the limits for eye lens equivalent dose as well as effective dose for the overwhelming majority of medical personnel. Again, an exception to this may be the few most exposed interventional radiologists, who may have eye lens doses close to the regulatory limits for radiation workers. For these few interventionalists, more accurate dosimetry and optimisation of radiation protection practices is required to ensure compliance to the regulatory limits for eye lens equivalent dose.

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