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— changes from 2008 to 2018 in Finland

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ACADEMIC DISSERTATION

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Academic dissertation

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Patient exposure levels and collective effective dose to the population from radiological examinations – changes from 2008 to 2018 in Finland

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Keywords: effective dose, collective effective dose, population dose, effective dose per caput, radiological examinations

Abstract

Medical exposures from x-rays and nuclear medicine (NM) have been the largest man-made source of population exposure to ionizing radiation in developed countries for many years. A collective effective dose can be assessed by summarizing effective doses from all radiological examinations together. The collective effective dose is the product of the mean effective dose in a group and the number of individuals in that group. The most common method to assess effective doses per radiological examinations is to use application specific measurable quantities that are multiplied by predefined effective dose conversion factors. Frequencies of radiological examinations can be surveyed by questionnaires.

In Finland the total collective effective dose from x-ray and NM procedures has increased 59% in 2008–2018, mainly due to the increase of collective effective doses from computed tomography (CT) and interventional radiology. The collective effective dose from NM examinations has slightly increased and its relative proportion is only 5% of the total collective dose from radiological examinations.

About 70% of the collective effective dose from x-ray examinations was caused by CT in 2018, while the proportion of CT procedures was only 17%. CT procedures are the major and increasing source of collective effective dose from x-ray procedures. While the use of new tissue weighting factors (ICRP 103) increases the population dose from plain radiography, it has minimal effect on the population dose from CT examinations.

There was a large amount of variation in the exposure levels and exposure parameters used for radiotherapy simulations. Patient exposure levels were generally much higher than those used for diagnostics. Exposure parameters

should be reviewed and optimized together with the exposure level also for radiotherapy CT simulations.

Effective doses per radiological examinations can be used to compare medical exposures from different methodologies or between different units or hospitals. Per caput doses can be compared between countries. In comparison with 36 European countries is was shown that frequencies of both x-ray and NM examinations in Finland were less than in average in Europe. This indicates that the level of justification in Finland is at least at the average European level. The comparison of per caput effective doses showed that the dose in Finland was on the lowest quarter among European countries. Despite of the increased collective effective dose from x-ray and NM examinations the overall per caput effective dose in Finland in 2018 was still well below the average of European countries in 2008 and only a third of the per caput effective dose in USA in 2016. This indicates that both justification and optimization of examinations in Finland is at a good European level.

Ritva Bly. Radiologisista tutkimuksista aiheutuvat potilasaltistusten tasot ja väestön kollektiivinen efektiivinen annos – muutokset vuodesta 2008 vuoteen 2018. STUK-A 265. Helsinki 2021, 104 s.

Avainsanat: efektiivinen annos, kollektiivinen efektiivinen annos, väestöannos, efektiivinen annos väestön yksilöä kohti, radiologiset tutkimukset

Tiivistelmä

Röntgentutkimuksista ja -toimenpiteistä ja isotooppitutkimuksista aiheutuva säteilyaltistus on ollut useita vuosia suurin keinotekoisen altistuksen lähde ionisoivalle säteilylle, kun arvioidaan koko väestön saamaa altistusta. Kollektiivista efektiivistä annosta voidaan arvioida yhdistämällä efektiiviset annokset kaikista radiologisista tutkimuksista.

Kollektiivinen efektiivinen annos saadaan kertomalla tutkimusryhmän keskimääräinen efektiivinen annos ryhmään kuuluvien tukittavien määrällä. Yleisin menetelmä radiologisesta tutkimuksesta aiheutuvan efektiivisen annoksen arvioimiseksi on käyttää menetelmäkohtaista mitattavaa suuretta, joka kerrotaan ennalta määritetyllä konversiokertoimella. Tutkimusmääriä voidaan selvittää kyselyillä.

Suomessa röntgentutkimuksista ja -toimenpiteistä ja isotooppitutkimuksista aiheutunut kollektiivinen efektiivinen annos kasvoi 59 % vuosina 2008–2018 pääosin tietokonetomografiasta (TT) ja toimenpideradiologiasta aiheutuneen kollektiivisen efektiivisen annoksen vuoksi. Isotooppitutkimuksista aiheutuva kollektiivinen efektiivinen annos on hieman suurentunut ja sen suhteellinen osuus vain 5 % kaikista radiologisista tutkimuksista aiheutuneesta kollektiivisesta annoksesta.

Noin 70 % röntgentutkimuksista ja -toimenpiteistä aiheutuneesta kollektiivisesta efektiivisestä annoksesta aiheutui TT:stä vuonna 2018, vaikka TT-tutkimusten suhteellinen osuus oli vain 17 %. TT-tutkimukset ovat pääasiallinen ja enenevä lähde röntgentutkimuksista ja -toimenpiteistä aiheutuvalle kollektiiviselle efektiiviselle annokselle. Vaikka uudet kudospainotuskertoimet (ICRP 103) lisäsivät tavanomaisista röntgentutkimuksista aiheutuvaa väestön

annosta, uusilla kertoimilla oli vain vähän vaikutusta TT:stä aiheutuvaan väestön annokseen.

Sädehoidon simulointia varten tehtävien TT-tutkimusten altistustasoissa ja säteilyparametreissä oli paljon vaihtelua. Potilasaltistusten tasot olivat yleisesti paljon korkeammat kuin diagnostiikasta aihetuvat altistustasot. Myös sädehoidon simuloinnin TT-tutkimusten säteilyparametreja pitäisi tarkastella ja optimoida yhdessä altistustasojen kanssa.

Radiologisista tutkimuksista aiheutuvia efektiivisiä annoksia voidaan käyttää vertailtaessa eri menetelmien aiheuttamia lääketieteellisiä altistuksia tai altistuksia eri yksiköiden tai sairaaloiden välillä. Väestön yksilöiden annoksia voidaan vertailla maiden välillä. Suomen tutkimusmäärät osoittautuivat 36 Euroopan maan vertailussa keskimääräistä pienemmiksi. Tämä antaa viitteitä siitä, että oikeutusarvioinnin taso on Suomessa vähintään keskimääräisellä eurooppalaisella tasolla. Väestön yksilöiden välillä tehty annosvertailu osoitti, että Suomessa annokset olivat Euroopan maiden joukossa pienimmässä neljänneksessä. Vaikka röntgentutkimuksista ja -toimenpiteistä ja isotooppitutkimuksista aiheutunut kollektiivinen efektiivinen annos yhteensä oli suurempi vuonna 2018, se oli silti alle Euroopan maiden vuoden 2008 keskitason ja vain kolmannes vastaavasta annoksesta USA:ssa vuonna 2016. Tämä antaa viitteitä siitä, että tutkimusten oikeutusarviointi ja optimointi Suomessa on hyvällä eurooppalaisella tasolla.

Contents

Original publications

This dissertation is based on the following publications and they will be referred to in the text by their Roman numerals.

I Bly R, Järvinen H, Korpela H, Tenkanen-Rautakoski P, Mäkinen A. Estimated collective effective dose to the population from X-ray and nuclear medicine examinations in Finland. Radiation Protection Dosimetry, 147 (1-2), 233-236; 2011.

II Bly R, Jahnen A, Järvinen H, Olerud H, Vassileva J. Collective effective dose in Europe from X-ray and nuclear medicine procedures. Radiation Protection Dosimetry 165 (1-4), 129-132; 2015.

III Toroi P, Kaijaluoto S, Bly R. Patient exposure levels in radiotherapy CT simulations in Finland. Radiation Protection Dosimetry, 167 (4), 602-7; 2015.

IV Bly R, Järvinen H, Kaijaluoto S, Ruonala V. Contemporary collective effective dose to the population from X-ray and nuclear medicine examinations – changes over last 10 years in Finland. Radiation Protection Dosimetry, 189 (3), 318-322; 2020.

The author took part in planning all the studies and mainly analyzed the results. The literature review and writing of the articles was also primarily performed by the author. The results of these studies have not been used in other Ph.D. dissertations.

List of abbreviations

AAPM	American Association of Physicists in Medicine
BSSD	European Council Directive 2013/59/EURATOM (Basic Safety Standard)
CT	Computed tomography
$CTDI_{vol}$	Volume CT dose index
$CTKI_{vol}$	Volume CT kerma index
DAP	Dose-area product
DDM	Dose Datamed
DLP	Dose-length product
DMS	Dose monitoring systems, Dose management systems
DRL	Diagnostic reference level
E	Effective dose
EFTA	European Free Trade Association
EU	European Union
EUROSTAT	European statistical office of the European Union
FDG	Fluorodeoxyglucose
HRCT	High resolution computed tomography
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units & Measurements
IR	Interventional radiology
IVU	Intravenous urography
k	Coverage factor
K, Kerma	Kinetic energy released per unit mass
K_e	Entrance surface air kerma
K_i	Incident air kerma
KAP, P_{KA}	Kerma-are product
KLP, P_{KL}	Kerma-length product
MED	European Council Directive 97/43/EURATOM (in relation to medical exposure)
MIRD	Medical internal radiation dose
MGD	Mean glandular dose
MoH	Ministry of Social Affairs and Health

MRI	Magnetic resonance imaging
NM	Nuclear medicine
PET	Positron emission tomography
NCRP	National Council on Radiation Protection and Measurements
NRPB	National Radiological Protection Board (UK)
PTCA	Percutaneous transluminar coronar angioplasty
RIS	Radiological Information System
S	Collective effective dose
SPECT	Single-photon emission tomography
STUK	Radiation and Nuclear Safety Authority in Finland
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

Aims of the study

The main purpose of the work presented in this dissertation was to assess the patient exposure levels and collective effective doses to the population from radiological examinations and to analyze changes from 2008 to 2018. The assessments were aimed to be carried out separately for x-ray and nuclear medicine procedures. Moreover, the patient exposure levels in radiotherapy CT simulations in Finland were supposed to be assessed for the first time and results to be compared to patient exposure levels in diagnostic radiology. The results of the per caput effective doses were compared to results from other countries to investigate at what level the Finnish doses are and if the level of justification and optimization of radiation protection could be indicated.

The specific aims of the research described in this dissertation were to:

1. assess the patient exposure levels in radiological examinations and in radiotherapy CT simulations (studies I, II, III, IV);
2. assess collective effective doses to the population from radiological examinations (studies I, II, IV)
3. study the level of optimization of protection in radiological examinations compared to other European countries, USA and Australia based on per caput doses (studies II, IV)

Study I
Bly R, Järvinen H, Korpela H, Tenkanen-Rautakoski P, Mäkinen A. Estimated collective effective dose to the population from X-ray and nuclear medicine examinations in Finland. Radiation Protection Dosimetry, 147 (1-2), 233-236; 2011.

Abstract: The collective effective doses to the population from x-ray and nuclear medicine (NM) examinations in Finland in 2008 and 2009, respectively, were estimated. The estimated collective effective dose per inhabitant was 0.45 mSv from x-ray examinations and 0.03 mSv from NM examinations. The collective effective doses per inhabitant have not changed substantially during the last 10 y. However, proportional dose due to CT

examinations has increased from 50% in 2005 to 58% in 2009 of the total collective effective dose from all x-ray examinations and proportional dose of PET examinations from 7 to 13% of the total collective effective dose from NM examinations. The collective effective dose from conventional plain radiography was over 20% higher when estimated using the new (ICRP 103) tissue weighting factors than that obtained using the old (ICRP 60) tissue weighting factors.

Study II
Bly R, Jahnen A, Järvinen H, Olerud H, Vassileva J. Collective effective dose in Europe from X-ray and nuclear medicine procedures. Radiation Protection Dosimetry 165(1-4), 129-132; 2015.

Abstract: Population doses from radiodiagnostic (x-ray and nuclear medicine) procedures in Europe were estimated based on data collected from 36 European countries. For x-ray procedures in all European countries included in the survey the collective effective dose is 605 000 manSv, resulting in a mean effective dose of 1.05 mSv per caput. For nuclear medicine in all European countries included in the survey the collective effective dose is 31 100 manSv, resulting in a mean effective dose of 0.05 mSv per caput.

Study III
Toroi P, Kaijaluoto S, **Bly R**. Patient exposure levels in radiotherapy CT simulations in Finland. Radiation Protection Dosimetry, 167 (4), 602-7; 2015.

Abstract: Computed tomography (CT)-based simulation is an essential part of the radiotherapy treatment process. Patient exposure levels in CT simulations were collected from 15 CT systems from all 13 Finnish radiation therapy centres. A large standard deviation up to 56% in dose levels between CT systems was noticed. Average volumetric CT dose indexes (in body phantom) were 24, 18 and 29 mGy for prostate, resection breast and head and neck treatment targets, respectively, and 70 mGy (in head phantom) for whole brain. These average dose indexes were much higher than those in corresponding diagnostic imaging in Finland. Dose levels in simulations with some devices were even over 3-fold higher than the diagnostic reference level for the same area of interest. Moreover, large variations in other exposure

parameters, such as pitch and slice thickness, were seen. The results were discussed nationally, and general guidance to optimize dose levels was shared.

Study IV
Bly R, Järvinen H, Kaijaluoto S, Ruonala V. Contemporary collective effective dose to the population from X-ray and nuclear medicine examinations – changes over last 10 years in Finland. Radiation Protection Dosimetry, 189(3), 318–322; 2020.

Abstract: Contemporary collective effective doses to the population from x-ray and nuclear medicine examinations in Finland in 2018 was estimated. The estimated effective dose per caput from x-ray examinations increased from year 2008 to 2018 respectively from 0.45 mSv to 0.72 mSv and from nuclear medicine examinations from 0.03 mSv to 0.04 mSv. The proportional dose due to CT examinations of the total collective effective dose from all x-ray examinations increased from 58% in 2008 to 70% in 2018 and the dose did not change substantially in total when new conversion factors were applied. The collective effective dose from conventional plain radiography did not change substantially during the last ten years while the new (ICRP 103) tissue weighting factors were taken into use in 2018, however frequencies of examinations in total decreased. The collective effective dose from CT in nuclear medicine tripled between 2009 and 2018.

1 Introduction

Radiological examinations are performed either by using ionizing or non-ionizing radiation and ultrasound. Ionizing radiation is used in x-ray and nuclear medicine procedures. Medical x-ray exposures have been the largest man-made source of population exposure to ionizing radiation in developed countries for many years and most of this contribution comes from diagnostic x-rays (above 90%) as reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2008). Imaging technology, especially for computed tomography (CT) and interventional radiology (IR), has developed rapidly (WHO 2000; UNSCEAR 2008). This development has improved health care by providing better imaging tools for diagnosis and treatment. Therefore, the number of relatively high-dose x-ray examination performed and collective effective dose to the population have increased (EC 2014b). Internationally it has been considered important for radiation protection that authorities make regular assessments of the radiological population exposures to be able to assess the trends and to compare situations in different countries.

European Council Directive 2013/59/EURATOM (BSSD) (EC 2014a) defines the legal requirements for radiation protection of individuals submitted to medical exposures in the European Union (EU). According to Article 64, the Member States shall ensure that the distribution of individual dose estimates from medical exposure for radiodiagnostic and interventional radiology purposes is determined for the population. The requirement has been transposed to the national legislation (Radiation Act 2018). A similar requirement was already in the Medical Exposure Directive 97/43/Euratom (EC 1997) and taken into Finnish legislation in 2000 (Ministry of Social Affairs and Health 2000).

X-ray procedures are dived to plain radiography, contrast enhanced radiography, CT and interventional radiology (IR). Examples of plain radiography examinations are chest x-rays and dental intraoral examinations. An example of contrast enhanced radiography is coronary angiography (CA). CT examinations are performed on different anatomical areas, most commonly on head and neck region, and percutaneous transluminar coronar angioplasty (PTCA) is the

most frequent IR procedure. In nuclear medicine procedures distribution of a radiopharmaceutical is imaged by a gamma camera, a single photon emission (SPECT) or a positron emission photon (PET) camera and in hybrid imaging there is also a simultaneous or sequential CT examination either for attenuation correction or for improving the visualization of the anatomy. In PET-MRI the anatomy is visualized by using magnetic resonance imaging, which is non-ionizing radiation. In radiotherapy a treatment plan is most often made based on CT imaging.

Radiation exposure that incurred by patients or asymptomatic individuals as part of their own medical or dental diagnosis or treatment is called medical exposure. Compared to other exposures it is unique that medical exposure is intentional and for the direct benefit of the patient. Medical exposures to patients from radiological examinations can be assessed using measurable dosimetric quantities that are related to radiation doses. In practice, patient doses cannot be measured directly, because detectors would need to be placed inside the human body.

A commonly used radiation protection quantity is effective dose. The effective dose is the weighted sum of the equivalent doses in all the tissues and organs of the body. The equivalent dose is the absorbed dose averaged over a tissue or organ and weighted for the radiation quality that is of interest. Effective dose provides a basis for estimating the probability of stochastic effects only for absorbed doses well below the thresholds for deterministic effects (tissue reactions). (ICRP 1991, ICRP 2007)

The most common method to assess effective doses per radiological examinations is to use application specific measurable quantities that are multiplied by predefined effective dose conversion factors. Application specific quantities are practical dosimetric quantities that are used for measurements in radiology. In diagnostic radiology the typical quantities are incident air kerma (K_i), entrance surface air kerma (K_e), kerma-area product (*KAP*), kerma-length product (*KLP*), volume CT air kerma index ($CTKI_{vol}$) and in nuclear medicine administered activity. (ICRU 1996, IAEA 2007, ICRP 2007a, ICRP 1998).

Effective doses per radiological examinations can be used to compare medical exposures from different methodologies or between different units or hospitals. A collective effective dose can be assessed by summarizing effective doses from all radiological examinations together. In case there is data on national level of all examinations, a collective effective dose to the population can be assessed.

Population doses can be compared between countries. That may show differences in practices to perform radiological examinations, but also differences in optimization of radiation protection.

The fundamental radiation safety objective is to protect people and the environment from harmful effects of ionizing radiation (IAEA 2006). The main principles for radiation safety are justification of medical exposure and optimization of radiation protection. The principal aim of medical exposures is to do more good than harm to the patient. For medical exposure a detailed approach of justification is needed. Based on recommendations by the ICRP, justification is performed on three levels. The ICRP considers that the first level of justification can nowadays be taken for granted (ICRP 2007b). It means that in general medical exposure is justified. On the second level a general justification of a specified procedure with a specified objective is needed to judge whether the radiological procedure will usually improve the diagnosis or treatment or will provide necessary information about the exposed individuals. Finally, on the third level of justification the application of the procedure to an individual patient should be justified in advance, considering the specific objectives of the exposure and the characteristics of the individual involved.

The principle of optimization of radiation protection is defined by the ICRP generally as follows: The likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors. According to the BSSD the optimization of the protection of individuals subject to medical exposure shall apply to the magnitude of individual doses and be consistent with the medical purpose of the exposure. In radiology and nuclear medicine, the aim is to minimize patient exposure whenever possible, while still using exposures that are high enough to produce images of good enough quality as to be able to provide a proper diagnosis. (ICRP 2007b, EC 2014b)

The assessment of collective effective doses to population and the follow-up of their trends in long term will provide important information to ensure that the optimization of protection is adequate in radiological examinations. It is also useful to determine the contributions of different imaging modalities, types of examination and their frequencies to the total collective effective dose from all medical examinations. Moreover, it is useful to make comparisons of population doses between different regions in the country and between other countries in which the level of health care is similar, such as European countries, United States

of America and Australia. It is also possible to compare the contribution from medical examinations with those from other natural and manmade sources of population exposure in a country.

2 Assessing medical exposure of patients

2.1 Effective dose

The fundamental dosimetric quantity in radiological protection is the absorbed dose. ICRP uses it generally to mean the average dose over a tissue or organ. The probability of stochastic effects depends on the absorbed dose and on the type and energy of the radiation causing the dose. This is taken into account by using radiation weighting factors. This weighted absorbed dose is an equivalent dose in a tissue or organ, also called organ dose. The relationship between the probability of stochastic effects and equivalent dose depends on the organ or tissue irradiated. The factor by which the equivalent dose in tissue or organ is weighted is called the tissue weighting factor, which represents the relative contribution of that organ or tissue to the total detriment due to these effects resulting from uniform irradiation of the whole body. (ICRP 1991)

The effective dose (E) is the tissue-weighted sum of the equivalent doses in all specified tissues and organs. Effective dose enables doses to be summed from whole and partial body exposure from external radiation of various types and from intakes of radionuclides. If only part of the body is irradiated, then only those regions are used to calculate the effective dose. Effective dose cannot be measured. The unit of E is joule per kilogram (J kg-1) and its special name is sievert (Sv). (ICRP 1991)

Tissue weighting factors take into account the variations in radiation sensitivity of different organs and tissues as for the induction of stochastic effects. Tissue weighting factors are based on epidemiological studies on cancer induction in exposed populations, and risk assessments for heritable effects. It is considered possible for radiological protection purposes to use age- and sex-averaged tissue weighting factors and that the system of protection is sufficiently robust to achieve adequate protection for both sexes. (ICRP 2007b)

The tissue weighting factors summate to 1.0, so that if an entire body is radiated with uniformly penetrating external radiation, the effective dose for the entire body is equal to the equivalent dose for the entire body. The latest tissue weighting factors from ICRP 103 (ICRP 2007b) consider newer epidemiological data on health effects of radiation than the previous ICRP 60 (ICRP 1991). The tissue weighting factor for the remainder tissues (0.12) in the ICRP 103 applies to the arithmetic mean dose of the 13 organs and tissues for each sex listed in the footnote to Table 1. In literature tissue weighting factors by ICRP 60 have been used for the latest estimations of collective effective doses in Europe (EC 2008, EC 2014b).

TABLE 1. Recommended tissue weighting factors by ICRP 60 and ICRP 103 (EC 2008, EC 2014b).

Organ	ICRP 60	ICRP 103
Bladder	0.05	0.04
Bone surfaces	0.01	0.01
Bone-marrow	0.12	0.12
Brain	within Remainder	0.01
Breast	0.05	0.12
Colon	0.12	0.12
Gonads	0.2	0.08
Liver	0.05	0.04
Lung	0.12	0.12
Oesophagus	0.05	0.04
Salivary glands	N/A*	0.01
Skin	0.01	0.01
Stomach	0.12	0.12
Thyroid	0.05	0.04
Remainder**	0.05	0.12
Total	1.00	1.00

*N/A means not available.**Remainder tissues: ICRP 60: Adrenals, Brain, Kidneys, Muscle, Pancreas, Small intestine, Spleen, Thymus, Upper large intestine, Uterus/Cervix. ICRP 103: Adrenals, Extrathoracic tissue, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate, Small intestine, Spleen, Thymus, Uterus/Cervix.

2.2 Use of effective dose in medical exposure

Effective dose is intended for use as a protection quantity. Effective dose is not recommended for epidemiological evaluations. Moreover, it should not be used for detailed specific retrospective investigations of individual exposure and risk. However, effective dose can be of value for comparing doses from different diagnostic procedures and for comparing the use of similar technologies and procedures in different hospitals and countries as well as the use of different technologies for the same medical examination. (ICRP 2007b)

In medial use of x-rays, the beam is delineated to reduce the exposure and to minimize the unwanted scattering and thus the radiation exposure of the body is not homogeneous. Additionally, the dimensions of the body vary a lot and therefore a measurement in one point in the body would not be adequate to determinate an equivalent dose or an absorbed dose to the organ. In nuclear medicine the distribution of activity is also heterogeneous and depends on the biokinetics of the radiopharmaceutical. It is not possible to compare different exposures without a common quantity and therefore, effective dose is a useable quantity for the purpose.

Typical mean effective doses in plain radiography range from 0.1–4 mSv and in contrast enhanced examinations 2–20 mSv. CT procedures result in effective doses in the range of 1–24 mSv and interventional procedures 5–22 mSv. A typical effective dose from the most common interventional procedure PTCA is 11 mSv. (EC 2008, EC 2014b)

2.3 Methods for assessing effective doses in medical exposure

Effective doses from radiological examinations to individual patients can be assessed based on measurable dosimetric quantities (see 2.3.1) and predefined effective dose conversion factors (see 2.3.2), or by using computational methods (see 2.3.3). The former is more approximative while also the most practical method whenever conversion coefficients are available. The latter is a more sophisticated approach that can provide more accurate values and can also be used for the determination of the conversion coefficients.

2.3.1 Dosimetric quantities

Patient exposure monitoring using the measurable dosimetric quantities can be based on either tube output measurements or measurements in standard phantoms. The tube output measurements define air kerma per tube loading for different radiation qualities. Patient exposure is calculated using the display of tube current and exposure time (STUK 2004). Phantom based measurements are convenient and using standard phantoms the results are comparable, however measurements do not give exposure data for individual patients or take in account the good or poor optimization of exposure levels for patients of different size and composition.

Typically, in the dosimetry of medical x-ray imaging the medium is air and the quantity used for measurements is air kerma (K_{air}). In the energy range of medical x-ray imaging there is an equilibrium of charged particles and K_{air} is almost equal to the absorbed dose to air. The incident air kerma (K_i) is used for the K_{air} from an x-ray beam measured on the central beam axis at the position of the patient or phantom surface. When the backscattering from the patient or phantom is included, this is called entrance surface air kerma (K_e) and it is used to provide a better estimate of the patient skin dose. The K_i can be directly measured or determined indirectly if the tube output and exposure parameters (tube voltage, tube loading, focus to skin distance, filtration and field size) are known for each patient undergoing x-ray examination. For mammography, the K_i is used together with the exposure parameters to assess mean glandular dose (MGD), because the glandular tissue is the most radiation-sensitive part of a breast. (ICRU 1996, IAEA 2007)

The kerma-area product (*KAP*, P_{KA}) of an x-ray beam is the surface integral of K_{air} over the area A of the entire beam in a plane perpendicular to the beam axis. This surface integral is often approximated by the product of the nominal area A of the x-ray field and the air kerma measured at the centre of the field. (ICRU 1996, IAEA 2007). Instead of *KAP*, a dose-area product (*DAP*) is often used, because K_{air} is almost equal to the absorbed dose to air (IEC 2019).

KAP may be used for the routine monitoring of patient x-ray exposure. Modern x-ray diagnostic and fluoroscopy machines are often equipped with built-in KAP meters. Alternatively, there may be devices which determine the *KAP* based on x-ray tube parameters, filtration and the setting of the diaphragm. The *KAP* is approximately invariant with distance from the x-ray tube focus, as long as the

planes of measurement are not so close to the patient or phantom that there is a significant contribution from backscattered radiation. (ICRU 1996, IAEA 2007)

For CT dosimetry, a volume CT kerma index ($CTKI_{vol}$) represents the average air kerma over the x, y, and z directions, considering specific information of each acquisition protocol (ICRP 2007a, IAEA 2007). IEC uses a volume CT dose index ($CTDI_{vol}$) that equals in CT imaging practice with $CTKI_{vol.}$ $CTDI_{vol}$ is the parameter that best represents the average absorbed dose at a point with the scan volume for a particular scan protocol for a standardized phantom (IEC 2009). For a complete examination taking into account the scan length, a CT air kerma–length product (KLP, P_{KL}) is calculated from patient exposure parameters and results of air kerma measurements in standard head and body CT dosimetry phantoms (ICRP 2007a, IAEA 2007). Instead of KLP, a dose-length product (DLP) is often used, because K_{air} is almost equal to the absorbed dose to air. A weighted KLP (KLP_w) can be measured directly, by using a special phantom suspension set-up so that the movement of the couch during examination does not disturb the measurement (Merimaa et al. 2010).

In diagnostic nuclear medicine patient exposure is estimated from administered activity and biokinetics of the used radiopharmaceutical. Time-activity curves after administration of labelled radiopharmaceuticals are prerequisite for biokinetic modelling. The administered activity is the normalization quantity when absorbed doses are assessed. Radionuclide activity meters (commonly known as dose calibrators) are used to measure the activity of radionuclides used in nuclear medicine. (ICRP 1988)

2.3.2 Effective dose conversion coefficients

Effective dose conversion coefficients are typically defined by Monte Carlo (MC) calculations using mathematical phantoms of which voxel phantoms are the latest developments. Physical measurements in anthropomorphic phantoms using for example TLDs is also possible. A list of some references for dose conversion coefficients for x-ray examinations is in the Table 2.

TABLE 2. A list of references for effective dose conversion coefficients for x-ray examinations.

Type of examination	Reference
Plain radiography	Drexler 1990 (GSF 11/90), NRPB-SR262, Tapiovaara 1997
Mammography	Dance 1990, Dance 2000, Wu 1994, Jansen 1994
Fluoroscopy	CDRH 92-8282, CDRH 95-8289, Tapiovaara 1997, Hart 2002
CT	NRPB-R250, NRPB-SR250, Zankl 1991 (GSF 30/91), AAPM 2008, Deak 2010, Christner 2010, Huda 2010, Huda 2011
Interventional radiology	McParland 1998

For nuclear medicine, ICRP has provided effective dose conversion coefficients. Effective doses per unit administered activity are constantly updated and new radiopharmaceuticals are included (ICRP 1988, ICRP 1998, ICRP 2008, ICRP 2015).

2.3.3 Computational methods

Effective doses arising from medical exposure in radiological examinations can be assessed most accurately by performing MC simulations based on mathematical phantoms that simulate patients. Exposure parameters and dosimetric data are needed as input parameters for these MC-calculations. Computational methods are needed also to provide the effective dose conversion factors discussed above (2.3.2).

Development of the computational methods has been fast over the last decades, when computing efficiency has improved. The ICRP provided in 2002 basic anatomical and physiological data for use in radiological protection reference values for the first time in a set of reference individuals (ICRP 2002) and the computational voxel phantoms of the reference male and reference female in 2009 (ICRP 2009) that are based on medical image data of real people. Voxel phantoms are computational anthropomorphic phantoms based on medical tomographic images where the anatomy is described by small three-dimensional volume elements (voxels) specifying the density and the atomic composition of the various organs and tissues of the human body. An organ dose value can be calculated as the mean value of all voxels assigned to the respective organ.

MC simulation and use of mathematical anthropomorphic phantoms is a powerful and flexible technique for estimating organ doses and effective doses to patients. An example of a solution that utilizes MC simulations is PCXMC

(Tapiovaara et al. 1997, Tapiovaara and Siiskonen 2008). It is a computer program for calculating patients' organ doses and the effective dose in medical x-ray examinations. It allows a free adjustment of the x-ray projection and other examination conditions of projection radiography and fluoroscopy. The input data can be for example incident air kerma or kerma-area product. The anatomical data are based on the mathematical hermaphrodite phantom models of Cristy and Eckerman, with some modifications and user-adjustable phantom sizes (Tapiovaara and Siiskonen 2008).

The constant increase of CT examinations and their major contribution to the collective effective dose has contributed to the development of solutions to estimate organ doses especially in CT imaging. Examples of using MC simulations in CT imaging are ImPACT (Shrimpton et al. 1993, Jansen and Shripton 2016), CT-Expo (Stamm and Nagel 2003) and CT Imaging (Kalender et al. 1999, Kalender 2014) that can be used to estimate scanner-specific organ doses. A more developed approach is POSDE (Kalender 2012) in which whole-body voxel phantoms are generated as a combination of patient and phantom data.

In nuclear medicine the absorbed doses received by the principal organs and tissues have been given in terms of absorbed dose per unit of administered activity. The calculations are based on biokinetic models and best estimates of biokinetic data for individual radiopharmaceuticals. The models were developed by the MIRD Committee of the United States Society of Nuclear Medicine and the dosimetry work performed at the Oak Ridge National Laboratory, Tennessee, USA. The models were subsequently adopted by the ICRP (ICRP 53, 1988). ICRP has updated the biokinetic and dosimetric data for new radiopharmaceuticals, and provided additionally effective doses per unit administered activity (ICRP 1998, ICRP 2007, ICRP 2015). In some cases, the absorbed dose is calculated by a more recent model than that provided by the MIRD. More precise dosimetry is mainly needed in radionuclide therapy in which MC calculations and voxel phantoms are used.

3 Assessing collective effective dose to the population

3.1 Definitions

The collective effective dose (S) is the product of the mean effective dose in a group and the number of individuals in that group. The special unit of S is man sievert (man Sv). With some reservations, S can be thought of as representing the total consequences of the exposure of a population or group. The pragmatic approach is discussed in the paragraph 3.5.

The collective effective dose S to the population can be approximated mathematically as follows:

$$S = \sum_i N_i E_i \,/1000, \qquad (1)$$

where N_i is the number of individuals experiencing an effective dose in the subgroup i and E_i is the mean effective dose to population in the subgroup i. The unit of E_i in radiological examinations is mSv and therefore, the E_i is divided by 1000 for unit conversation.

A subgroup here means a type of examination according to the classification of examinations used. In practice, it is typical that some individuals have several examinations in a given subgroup, but in the assessment of the collective effective dose only the number of examinations is then relevant and it is used here equal to N_i.

The average effective dose per caput ($E_{per\ caput}$) can be approximated mathematically as follows:

$$E_{\text{per caput}} = \frac{S}{P} \cdot 1000, \qquad (2)$$

where P is the number of the individuals (i.e. size of the population).

The unit of the $E_{\text{per caput}}$ is mSv.

The time period and number of individuals over which the effective doses are summed should always be specified. In assessing collective effective dose for comparative purposes, the time period is typically one year.

3.2 Frequencies of examinations

In the formula (1) N_i must be estimated based on numbers of examination in a subgroup i performed in a specified time period. The numbers in a specific time period are also called frequencies. The subgroups are different categories of examinations such as plain radiography or CT and even within these subgroups there may be more specific categories such as chest x-ray or CT of brain. In nuclear medicine the categorization needs to consider the radionuclide, pharmaceutical, procedure of the examination and the possible use of CT.

The recommended definition of an x-ray examination in EU RP 154 (EC 2008) is: 'An x-ray examination or interventional procedure is defined as one or a series of x-ray exposures of one anatomical region/organ/organ system, using a single imaging modality (i.e. radiography/fluoroscopy or CT), needed to answer a specific diagnostic problem or clinical question, during one visit to the radiology department, hospital or clinic'.

The broad categories of specific types of examinations or procedures are typically (UNSCEAR 2008, EC 2008, NCRP 2019):

1. Projection radiography (without contrast media)
2. Radiography/fluoroscopy (mostly involving contrast)
3. Computed tomography
4. Interventional procedures.

Moreover, NCRP (National Council on Radiation Protection and Measurements) has divided interventional procedures to cardiac and non-cardiac procedures. Within these broad categories examinations are typically arranged according to the region of the body or the organs/tissues being imaged.

The information of the numbers of examinations performed can be obtained from the Radiology Information Systems (RIS) that are widely used in developed

countries or from national health insurance databases. In most countries, predefined code systems are used to describe the categories of x-ray examinations that take place. In case the code system is designed to meet national systems for reimbursement the system may not be ideal for categorization of examinations for assessing collective effective dose. (EC 2008)

The data may also be collected by electronic surveys or allowing a use of paper forms if required. The globally widest survey is performed by UNSCEAR based on electronic surveys to collect data from national radiation protection authorities. (EC 2008; UNSCEAR 2008)

Frequencies of radiological examinations in a whole population may also be estimated based on samples. A sample may origin from a regional area in a country or from a certain type of a hospital. Samples may also represent only certain types of examinations. Effects of a limited sample size and other important sources of uncertainty in the frequency and typical effective dose estimates are discussed in the paragraph 3.6.

Very rough estimates of frequencies of radiological examinations can be also made by using secondary information such as number of physicians in the country. Moreover, some data may be completed by information on frequencies in other countries of a similar health care level. (UNSCEAR 2008, EC 2014b)

3.3 Effective doses of categorized examinations

In the formula (1) E_i must be estimated to each subgroup i. In case there are only few broad categories the estimated value of the average effective dose can only be a very rough estimate, because there is a lot of variation between different types of examinations. However, it might be difficult to collect data for hundreds of subgroups and to determine the mean effective dose (E_i) for each subgroup.

Mean dosimetric data can be estimated by surveying measurable dosimetric quantities of patient examinations from data bases or making data collections of dose display values or exposure parameters. Similar data may be collected for setting up diagnostic reference levels that is a requirement in the BSSD and in the International Basic Safety Standards (IAEA 2014) and utilized also for estimating effective doses.

Typically, the effective doses are calculated using the selected conversion factors from literature for x-ray examinations (Table 2) and for NM examinations

(ICRP 1988, ICRP 1998, ICRP 2008). The mean dosimetric value is multiplied by an appropriate effective dose conversion coefficient. Alternatively, in case there is no other means to get the information on mean effective doses, predefined values from literature (EC 2008) may be used.

3.4 The average effective dose per caput

Since the collective effective dose to the population depends on the size of the population, it is often more useful to use the annual average per caput effective dose (i.e. the annual collective effective dose averaged over the entire population) as defined in the formula (2). This is useful particularly when studying trends in population doses over time and there are changes in the number of individuals or when comparing the population doses of different countries. UNSCEAR has used population doses expressed in terms of the annual collective effective dose or the annual average per caput effective dose (UNSCEAR 2008). It is also possible to compare the contribution from medical exposures with those from other natural and manmade sources of population exposure in a country (UNSCEAR 2008, STUK 2020).

3.5 Practical methods for assessing collective effective dose to the population

In practice the assessment of the collective effective dose to the population has following steps:

1. Defining the categorization of examinations
2. Collecting the data or samples on frequencies of examinations and typical effective doses
3. Combining the data from different sources or samples to establish a database on frequencies
4. Assessing the effective doses for each categories of examinations
5. Assessing the collective effective dose to the population
6. Assessing the effective doses per caput.

The most complete method for estimating population doses is a combination of a very detailed categorization of examinations, a collection of frequencies from all clinics for all categories of examinations and an estimation of effective doses to each specified category of examinations. In practice, this might be difficult to achieve and therefore, the population dose need to be estimated based on a limited number of broader categories and some frequencies may need to be scaled from samples to cover the full population.

The guideline (EC 2008) proposes the method of categorization of x-ray examinations and procedures for the calculation of the population dose. The most detailed categorization includes 225 categories that are specified in a more complete way by defining what kind of examinations should be included into each category. The ten EU countries that contributed to the guideline had a narrower categorization, with 70 categories. In addition, the guideline presents 20 groups which, according to a study conducted in the above-mentioned ten EU countries, account for 50–70% of all x-ray examinations and procedures and cause 70–90% of the total collective effective dose to the population for all x-ray examinations and procedures.

According to the EU guideline, in countries where it is not possible to make a calculation of the population dose based on a more detailed grouping, the dose of the population can be estimated by making a calculation for the 20 most important groups of examinations and procedures (TOP 20 method). Thus, the TOP 20 method is less accurate than methods based on more complete categorizations of examinations and only gives an approximate estimate of the collective effective dose to the population.

For the determination of the collective effective dose, the general population has been used instead of the patient population, and no distinction has been made between adult and paediatric populations. This pragmatic approach is justified for several reasons related to the availability and comparability of the data and the deficiency of effective dose as a risk quantity for patient population. For a more comprehensive approach a national data register would be a prerequisite including clinical data on radiological procedures.

3.6 Uncertainties in estimating population doses

Uncertainties in estimating population doses can be systematic or random. Systematic errors may due to several reasons related to data collection. The greatest source of uncertainty is the limited sample size of frequencies and effective doses (UNSCEAR 2008). Typically, the uncertainties are estimated at the 95% confidence level with a coverage factor k of 2.

Important sources of uncertainty in the frequency estimates include (EU RP 154, UNSCEAR 2008):

1. Problems in relating the information stored in terms of examination codes into actual numbers of examinations (e.g. inadequate definition of an "examination", problems of double-counting, for example, a cardiac nuclear medicine procedure consisting of rest and exercise phases may be systematically recorded as one or two examinations).
2. Insufficiently differentiated codes (the specified categories are not determined clearly and if there are not enough categories).
3. Bias in the sample and invalid assumptions made when scaling up sample data to derive frequencies for the whole population (i.e. problem of using data from an unrepresentative sample of hospitals or from incomplete central statistics).
4. Lack of frequency data from some important providers of radiology services (e.g. interventional procedures performed outside x-ray departments or fluoroscopy performed in operating theatres and therefore not recorded by the RIS, or dentists in private practice that are not covered by central statistics).
5. Mistakes in the data recorded or collected.

The uncertainty of frequencies is highly dependent of the above mentioned factors and could be in a well organized data collection of several hundred categories of examinations about 0.1–2% at the best.

The important sources of uncertainty in the estimates of typical effective doses for each type of examination include (EC 2008, UNSCEAR 2008):

1. Uncertainties in the basic dose measurements; uncertainties about 10–20% are likely to apply to individual basic dose measurements, but even 7% is achievable (ICRU 1996). The uncertainties in the basic dose measurements are small compared to the variation in measured dose quantities of a sample of patients undergoing the same examination in the same hospital (Kelaranta et al. 2016). However, this variation between patients is not that relevant, because the *E* is defined for a standard patient.
2. Uncertainties due to variations in patient doses between hospitals and the limited sample size; the uncertainties of basic dose measurements are included. Approximate uncertainties in the estimated mean value vary from 10% (more than 100 equipment covered in the data collection) to 50% (5–19 equipment covered in the data collection) (Hart and Wall 2002). For small countries with a total number of equipment near the above mentioned sample sizes the uncertainties of this source will be much smaller.
3. Uncertainties in the coefficients used to convert the measured dose quantities into typical effective doses. For many of the common x-ray examinations, conversion coefficients have been calculated with exposure conditions closely matching the average used in clinical practice, so the uncertainties should be small, no more than about 10%. For other less common examinations the match will not be so good and uncertainties could rise to about 25%. (EC 2008)

The overall uncertainty of a mean effective dose for the examination can be estimated by summing in quadrature the uncertainties of sample size and conversion coefficients. The overall uncertainty may vary from 14% (for more than 100 equipment) to 56% (5–19 equipment). In case of using only data from other countries the overall uncertainty may be even 100%.

The overall uncertainties of population doses for the examinations can be estimated by summing in quadrature the uncertainties of frequencies and mean effective doses. In case, when uncertainties of frequencies are very small, the overall uncertainties of population doses are close to estimated overall uncertainties of mean effective doses.

Some random mistakes cannot be avoided, but they can often be reduced. For example, a large sample size reduces the uncertainty. Moreover, if there are time

series of data sets a comparison between them may reveal some typing errors or other kind of random mistakes. On the other hand, the assessment of time series of frequencies enables one to keep these uncertainties at least constant, and thus to recognize any trends in the frequency of x-ray examinations with time as early and as reliably as possible. (EC 2008)

4 Materials and methods

The collective effective doses to the population from x-ray and NM examinations in Finland in 2008 and 2009, respectively, and contemporary collective effective doses to the population in 2018 were estimated (Study I and IV). The changes in different examination groups over ten years were described taking into account changes in tissue weighting factors by ICRP. The results from 2008 and 2009 were also compared to results of 35 other European countries, United States and Australia (Study II). The European countries were EFTA countries that consisted of 28 EU member states (except Lichtenstein), Iceland, Norway and Switzerland, and other European countries that were Moldova, Montenegro, Former Yugoslavian Republic of Macedonia, Serbia and Ukraine. Moreover, patient exposure levels in CT simulations for radiotherapy were estimated in 2014 (Study III).

4.1 Collection of frequencies of examinations

Radiological examinations in Finland are categorized according to the national coding system by the Finnish institute for health and welfare (Kuntaliitto 2018) (Study I, II and IV). The system consists of 12 main broad categories (Table 3) and several predefined codes within each category, in total 1312 codes in 2018 of which 714 and 208 for x-ray and nuclear medicine examinations respectively. For some procedures there are two or three different codes depending on the complexity of the procedure. Moreover, there are 29, 94 and 30 codes in the broad category W of ancillary activities of radiological examinations, category X to complete other broad categories and category Y for radiotherapy treatment planning with computed tomography, respectively. In nuclear medicine the radiopharmaceutical is not included in these codes but an additional code was given in 2018 for 57 and 153 radiopharmaceuticals for SPECT and PET examinations, respectively. The coding system allows to develop more codes by the user if needed.

TABLE 3. Main broad categories of the Finnish coding system for x-ray and nuclear medicine examinations and number of specified codes in 2018. (Kuntaliitto 2018)

Name of the broad category		Number of specified categories in 2018
A	Plain radiography	127
B	Contrast enhanced radiography	29
C	Contrast enhanced examinations on vessels	57
D	Computed tomography (CT)	193
I	Cone beam computed tomography	32
E	Ultra sound (US)	185
G	Magnetic resonance imaging examinations (MRI)	176
N	Gamma imaging and single photon emission tomography (SPECT)	94
Q	SPECT-CT	31
R	PET-CT	39
S	PET-MRI	44
T	Interventional radiology	276

This Finnish coding system is very broad compared to other European coding systems (EC 2014b) (Study II). Only in the United Kingdom the system is even broader with 3220 specified categories. European Commission has recommended a system of 225 specified categories if there is no other system in place (EC 2008).

The frequencies of examinations classified according to the Finnish coding system were collected by questionnaires sent to all x-ray and NM units in Finland (Tenkanen-Rautakoski 2010, Bly et al. 2011, Ruonala 2019, Kaijaluoto and Liukkonen 2020). The response rates were 97% and 100%, respectively for surveys of 2008 and 2009 data, respectively (Study I). For surveys of 2018 data the response rates were 98% for radiology departments and private clinics, 91% for dental practices, 60% for radiotherapy units performing dose planning or simulation CT and 100% for NM departments (Study IV). A correction factor was applied to take into account the procedures not included in the survey by assuming that the missing data was equal to the collected data. Surveyed frequencies were weighted to correspond to 100% response rates.

Similar data on frequencies was collected from 35 other European countries in a project that was funded by European Commission (Study II). The collection was carried out using electronic questionnaires and Excel sheets that were sent

to national contact persons identified for the project. Templates of those Excel spreadsheets were integrated into the on-line system for download and the completed files were collected there within an integrated upload feature.

4.2 Estimation of mean effective doses of examinations

The average effective doses for plain radiography were calculated using PCXMC programme. Data from totally 1000 examinations were collected in 2006 from randomly selected 35 hospitals. For the estimation of effective doses in 2008 and 2018 ICRP 60 and ICRP 103 tissue correction factors were applied, respectively. (Study I and IV)

In contrast enhanced radiography and interventional radiology, the mean effective doses are based on typical *KAP* values or in few cases effective doses from literature (Study I, II and IV). *KAP* values in 2008 for barium enema, barium follow and endoscopic retrograd cholangiopancreaticography were based on data collection from two hospitals, but only from 14–20 patients. Barium meal is very rare in Finland but mean effective dose from literature was used (EC 154). *KAP* values in 2008 for CA and PTCA were based on data collection from one hospital covering procedures for 46 and 36 patients, respectively (Järvinen 2016). *KAP* values in 2018 for CA and cardiac interventional radiology including PTCA were based on data collected in 2014–2016 from over 18 000 procedures (Järvinen et al. 2018).

The mean effective doses for CT examinations from 2008 were based on STUK measurements of KLP_w in a standard phantom for most common procedures (head, lung, abdomen, lumbar spine) (Karppinen and Järvinen 2006) (Study I, II and IV). From the Finnish CT equipment in 2005, 80% were measured. The method was to cover the whole procedure in a single measurement. The average KLP_w values were defined, and the mean effective doses calculated for each procedure taking into account the type of the CT equipment (1, 2–4, 6–10 and 16 and more slice CT). Typically, in health centres and district hospitals mainly 1-slice CT were used, but university hospitals were equipped with 2–4 and 16 slice devices. Concerning procedures that induced at least 3% of the collective effective dose from all CT procedures, the distribution of procedures in different types of hospitals was taken into account in estimation of the effective dose. In case of a

very complex procedure the mean effective doses from normal procedures were multiplied by a factor of 2. The conversation coefficients were taken from the literature (Shrimpton et al. 2005).

The mean effective doses for CT examinations in 2018 were based on mean *KLP* values collected in 2012 for 12 procedures from 41 radiology departments of totally 57 CT units (Lajunen 2015) (Study IV). The CT devices were mostly 64-slice CTs. The correctness of dose displays of the CT equipment were verified by measurements during STUK's regular inspections. The mean effective doses from normal procedures were multiplied by a factor of 2 for very complex procedures.

To estimate exposure levels for CT simulations a questionnaire was sent to all 13 Finnish radiation therapy centres in 2014 (Study III). Data for a minimum of 10 average-sized patients (weights of 60–90 kg) were requested, including displayed $CTKI_{vol}$ and *KLP* values in CT simulations and information on the phantom used for dose display calibration. Other exposure parameters such as pitch, collimation, dose modulation, etc. were also requested. The survey covered the following treatment targets: prostate, resection breast, head and neck and whole brain. Doses for whole brain scans have been documented based on the head phantom (IEC 2009). If the result was given for the body phantom, it was multiplied by a factor of 2. Doses for scans of all other targets were documented based on the body phantom. If the result was given for the head phantom, it was divided by the factor of 2. The use of this technical correction factor of 2 can be justified e.g. based on the results of AAPM (AAPM 2011).

Mean effective doses for NM examinations were calculated based on reported mean administered activities and the conversion coefficients given by ICRP (ICRP 1988, ICRP 1998, ICRP 2008) (Study I, II and IV). Mean effective doses to the CT component in the SPECT-CT and PET-CT examinations were calculated based on literature (EC 2008) (Study IV).

The influence on the mean effective doses from the change in the ICRP tissue correction factors from ICRP 60 to ICRP 103 was investigated for projection radiography in the Study I. The effective dose conversion coefficients for CT examinations using ICRP 60 and ICRP 103 tissue weighting factors were compared in the Study IV.

4.3 Estimation of collective effective doses

The collective effective doses to the population from x-ray and NM examinations in 2008 and 2009 respectively, were estimated using the most complete method by using the national coding system and Top 20 method. Categorizing of examinations for the latter was done in co-operation with a consultative radiologist. The collective effective doses to the population in 2018 were estimated only using the most complete methodology.

In the European wide study, the overall collective effective dose was determined using the most complete method for only six countries (Bulgaria, Finland, France, Germany, Switzerland and United Kingdom) (Study II). For the other countries, which could report only Top 20 data, the overall collective effective dose was obtained from the Top 20 total collective effective dose by using a correction factor that takes into account the procedures not included in the Top 20.

In the comparison of the collective effective dose to the Finnish population from radiological examinations only the most complete method has been applied (Study I and IV). The pragmatic approach explained in Section 3.5 has been used in the Study I, II and IV, i.e. the collective effective dose has been determined for the general population with all ages included.

For the calculation of per caput effective dose, the population of 5.32 million (in the end of 2008), 5.35 (in the end of 2009) and 5.52 million (in the end of 2018) was used (Study I, II and IV).

5 Results

5.1 Frequencies of examinations

The frequencies of x-ray examinations per 1000 population in Finland in 2008 and 2018 of plain radiography (excluding dental examinations), contrast enhanced radiography, CT and interventional radiology are presented in Table 4 (Study IV) and frequencies of dental examinations in Table 5 (Tenkanen-Rautakoski 2010, Ruonala 2019). Results of a comparison of the frequencies among 36 European countries including Finland are shown in Figure 1 (Study II). On average a European citizen has one x-ray examination per year which applies also to Finland.

TABLE 4. The change of frequencies of x-ray procedures per 1000 population and contributions to total frequency in years 2008 and 2018 (Study IV).

Frequencies per 1000 population				Contribution to total frequency (%)	
Group procedures			Change (%)		
	2008	2018		2008	2018
Plain radiography*	658	542	-18	89.3	80.7
Contrast enhanced radiography	12.3	9.6	-22	1.7	1.4
Computed tomography	61.0	111	81	8.3	16.5
Interventional radiology	5.5	9.2	67	0.8	1.4
Total	**737**	**671**	**-9**	**100**	**100**

* Excluding dental procedures

TABLE 5. The change of frequencies of most common dental examinations per 1000 population in years 2008 and 2018.

Frequencies per 1000 population			
Group procedures			**Change (%)**
	2008	**2018**	
Intraoral dental examinations	396	357	-10
Panorama examinations	70	85	21
Cephalometry	-	8	-
Total	**466**	**450**	

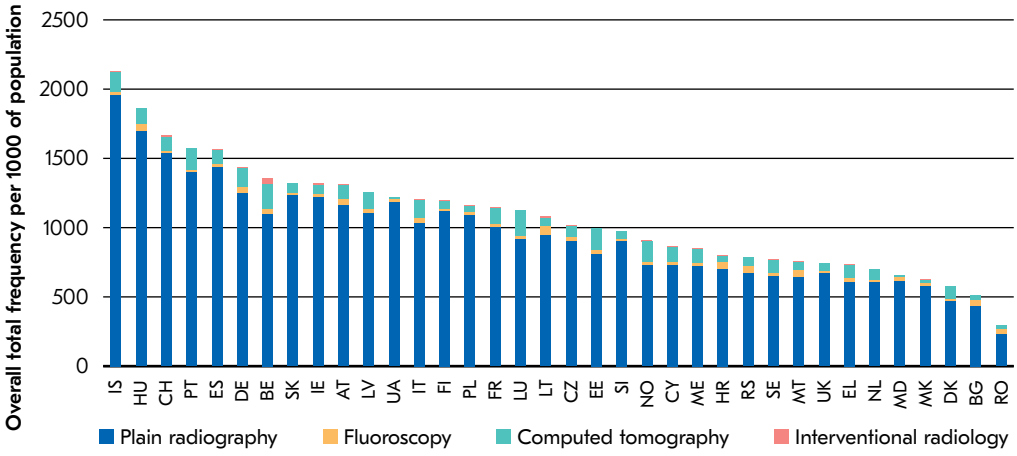

FIGURE 1. Frequencies per 1000 of population for different countries. The relative contributions of the four main groups: plain radiography (including dental), fluoroscopy CT and interventional radiology, are also shown (Study II) (EC 2014b).

The relative contributions of groups of procedures to the total frequency are shown in Table 4. The increase of frequencies of CT procedures from 2008 to 2018 was remarkable, 81% (Table 4). (Study IV)

The frequencies of both the plain radiography (excluding dental examinations) and contrast enhanced radiography and their contributions to the total frequency decreased, while that of interventional radiology considerably increased (Table 4). The total frequencies of dental examinations per 1000 inhabitants decreased from

466 to 450 (3%), but the frequency of panorama examinations increased 21% (Table 5).

The contribution of interventional radiology to the total frequency remained very small (1.4%) like that of contrast enhanced radiography. The most frequent interventional radiology procedure in 2018 was PTCA, which share was 22% within the group. Other notable interventional procedure that contributed remarkably to the collective effective dose was blockage of nerve root with CT guidance, which share was only 3% of the total frequency within the group. The most frequent contrast enhanced examination in 2018 was cardiac angiography, which share was 66% of all contrast enhanced examinations of vessels and 47% of all contrast enhanced examinations. (Study IV)

Frequencies of all NM examinations, all SPECT-CT and PET-CT procedures per 1000 inhabitants in Finland and the proportion of PET-CT procedures of all diagnostic NM procedures in 2009 and 2018 respectively are shown in Table 6 (Study I and IV). The frequency of the most frequent examination in 2018, an upper body or whole-body metabolic PET-CT with ^{18}F-FDG, was 1.3 per 1000 population (Study IV). The PET-CT procedures in 2018 were mainly for adults, since only 74 paediatric PET-CT procedures were performed. Moreover, the frequency of PET-CT represents about 8% and 30% of all diagnostic NM procedures in 2009 and 2018, respectively. (Study IV; Study II; Kaijaluoto and Liukkonen 2020) Frequencies of NM examinations in 36 European countries per 1000 inhabitants are shown in Figure 2. In Finland the frequencies of NM examinations are among the lowest in Europe.

TABLE 6. The change of frequencies of all NM procedures, SPECT-CT and PET-CT procedures per 1000 population and proportion of PET-CT procedures of all NM procedures in years 2009 and 2018 (Study I and IV).

Year	Frequency of all NM examinations per 1000 population	Frequency of all SPECT-CT procedures per 1000 population	Frequency of all PET-CT procedures per 1000 population	Proportion of PET-CT procedures of all diagnostic NM procedures (%)
2009	8.1	0.5	0.7	8
2018	7.7	1.6	2.2	28
Change (%)	-5	216	239	-

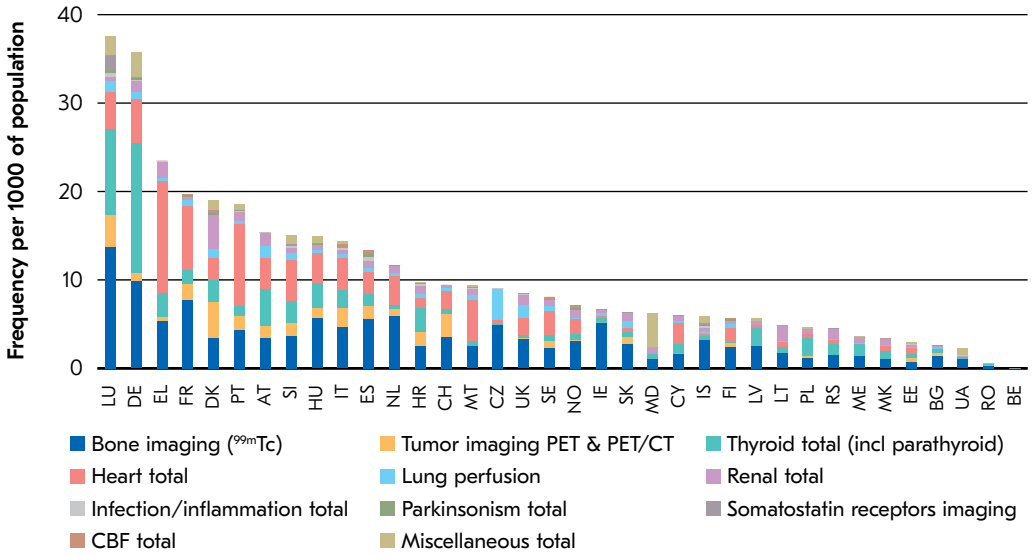

FIGURE 2. Frequencies of NM examinations in 36 European countries (Study II) (EC 2014b).

5.2 Mean effective doses

Typical mean effective doses that were used in the Study I, II and IV for plain radiography and CT examinations are given in Table 7 for Top 20 procedures, in Table 8 for some specific CT examinations, in Table 9 for the most important contrast enhanced procedures, in Table 10 for the most important cardiac procedures and in Table 11 for most relevant NM procedures in relation to collective effective dose. The typical mean effective doses used in 2008 for each examination code can be found in the STUK-TR-21 report (Järvinen 2016). The differences between mean effective doses in 2008 and 2018 are presented in the Study IV.

For plain radiography the basic imaging data for estimating mean effective doses for x-ray examinations was unchanged from 2008 to 2018, but there was a change in applying ICRP 103 tissue weighting factors for 2018 data for TOP 20 examinations no. 1–7 in Table 7 (Study I and IV).

For contrast enhanced radiography the mean effective doses from 2008 in STUK-TR-21 report (Järvinen 2016) were used also for estimation of collective

effective doses in 2018 (Study IV). A comparison of data from ten European countries is available in the EC RP 154 (EC 2008).

The differences in typical effective doses for CT examinations from 2008 to 2018 includes both changes in tissue weighting factors (Table 7 and 8) and in imaging techniques (Table 8) (Study IV). Imaging techniques include both the CT equipment and complexity of the procedure that are described in detail in the Section 4.2. The typical effective doses in Table 8 are based on the mean *KLP* values collected in 2012 (Lajunen 2015). The values for specific CT examinations were used prior to values in Table 7, as appropriate. The most complete method that has been used in parallel with the Top 20 method has more detailed coding within each broad Top 20 category and the complexity of the procedure has also been taken into account as described in Section 4.2. The coding of Top 20 method and more detailed coding can be found in the STUK-TR-21 report (Järvinen 2016).

TABLE 7. Typical effective doses for plain radiography and CT Top 20 procedures in 2008 by using ICRP 60 tissue weighting factors and in 2018 by using ICRP 103 tissue weighting factors (Study I and IV). The basic imaging data is the same in 2008 and 2018.

Top 20 no.	Procedure	Typical effective dose by ICRP 60 tissue weighting factors (mSv)	Typical effective dose by ICRP 103 tissue weighting factors in 2018 (mSv)	Difference (%)
1	Chest	0.07	0.09	29
2	Cervical spine	0.11	0.22	100
3	Thoracic spine	0.39	0.41	5
4	Lumbar spine	0.81	0.72	-11
5	Mammography	0.20	0.47	135
6	Abdomen	0.80	0.72	-10
7	Pelvis and hip	0.34	0.28	-18
13	CT-head	1.23	1.28	4
14	CT-neck	1.32	1.47	11
15	CT-chest	3.87	4.50	16
16	CT-spine	10.32	7.22	-30
17	CT-abdomen	6.67	7.25	9
18	CT-pelvis	14.48	6.19	-57
19	CT-trunk	8.78	10.12	15

TABLE 8. Typical mean effective doses for some specified CT examinations by using effective dose conversions coefficients based on ICRP 103 tissue weighting factors. (Lajunen 2015) (Study IV)

CT examination	Mean *KLP* values (Gy cm)	Typical effective dose by ICRP 103 based conversion coefficients in 2018 (mSv)
Skull base	273	0.52
Head other than skull base	672	1.28
Orbita	111	0.21
Facial trauma	246	0.47
Sinuses	150	0.28
Face other than sinuses	283	0.54
Lung embolia	227	3.29
Lung tumor	311	4.50
HRCT*	133	1.93
Lung other	293	4.25
Aorta (neck-pelvis)	609	8.82
Aorta (partial)	471	6.84
Urinary track stone	298	4.56
Trunk, lymphoma	854	12.38
Trauma	1067	15.48
Colonoscopy	363	4.68

*High resolution CT

TABLE 9. Typical mean effective doses for contrast enhanced radiography (Järvinen 2016) (Study I and IV)

Examination	Total *KAP* (mGy cm^2)	Typical mean effective dose (mSv)
Barium enema	9268	2.6
Barium follow	2843	0.63
Intravenous urography	–	2.4
Endoscopic retrograd cholangiopancreaticography	2767	0.72

TABLE 10. Typical mean effective doses for cardiac angiography (CA), pacemaker installation, transcatether aortic valve implantation (TAVI) and percutaneous transluminar coronar angioplasty (PTCA). Effective dose conversion coefficients from NRPB (Hart and Wall 2002) have been used both in 2008 and 2018 (Study I and IV).

Examination	*KAP* (2008) (Gy cm^2)	Typical mean effective dose 2008 (mSv)	*KAP* (2018) (Gy cm^2)	Typical mean effective dose 2018 (mSv)
CA	50*		22***	2.64
Pacemaker installation	7**	0.7	3***	0.3
TAVI	–	–	67***	9.4
PTCA	93*	24.2	64***	16.6
PTCA, complex procedure	93*	24.2	80***	21.0

* (Järvinen 2016), ** (Hart and Wall 2002), *** (Järvinen et al. 2018)

Typical mean effective doses for nuclear medicine examinations are given in Table 11 (Study I and Study IV). In heart examinations and some total body bone examinations a low dose CT procedure is used for attenuation correction. In 2008 CT was rarely used and mostly it was used for attenuation correction (Study I). In 2018 a mean effective dose from CT in NM was 1.8 mSv (Kaijaluoto and Liukkonen 2020).

TABLE 11. Typical mean effective doses for five procedures that contributed most to the collective effective dose from NM in 2018 (Study IV).

Examination	Mean effective dose from radionuclide (mSv)	Mean effective dose from CT* (mSv)	Total mean effective dose from examination (mSv)
Total body bone isotope imaging/^{99m}Tc phosphate or phosphonate	3.2	–	3.2
Whole body bone SPECT-CT/^{99m}Tc phosphate or phosphonate	2.5–2.7	1.8–9.7	4.3–12.4
Heart perfusion SPECT-CT at rest and with exercise/^{99m}Tc tetrofosmin	8.0	1.6	9.6
Upper body or whole body metabolic PET-CT/^{18}F-FDG	4.9	3.7–4.1	8.6–9.0
Whole body extensive metabolic PET-CT/^{18}F-FDG	5.8	10.6	16.4

* Reference for effective dose conversion coefficients of CT is EC RP 154 (EC 2008)

5.3 Exposure levels in radiotherapy CT simulations in Finland

In Study III data was collected from all 13 radiotherapy hospitals in Finland and for 15 CT systems. There was no clear correspondence between dose level and CT device type or manufacturer. Both lower and higher dose levels were observed for each CT manufacturer with several CT device. There was no clear correspondence between dose levels and the selected exposure parameters, such as tube voltage, field of view, pitch or slice thickness.

$CTDI_{vol}$ values for radiotherapy simulations of prostate, resection breast, head and neck, and whole brain are given in Table 12. The mean (typical) effective doses were calculated using dose conversion factors from Table 16. Typical effective doses are about 2–4 times higher than the values for other CT examinations (Tables 7 and 8).

TABLE 12. $CTDI_{vol}$ values for radiotherapy simulations (Study III) and estimated typical effective doses from average $CTDI_{vol}$ and length of the imaging area (scan length)

Target	Average $CTDI_{vol}$ (mGy) values (min—max)	Length of the imaging area (cm)	*E/KLP** (mSv/mGy cm)	Typical effective dose (mSv)
Prostate	24 (6—43)	34	0.0129	10. 5
Resection breast	18 (6—38)	36	0.0146	9.5
Head and neck	29 (9—45)	25 head + 11 neck	0.0019 head 0.0052 neck	5.0
Whole brain	70 (33—107)	25	0.0019	3.3

*From Table 16, based on ICRP 103 tissue weighting factors.

5.4 Collective effective doses

The collective effective doses and per caput doses from all x-ray and NM examinations in 2008 (x-ray), 2009 (NM) and 2018 are given in the Table 13 (Study I, Study II and Study IV). The time period for the collective effective doses is one year. Since 1997 to 2008 the effective dose per caput from all x-ray procedures had not varied much from 0.5 mSv, but until 2018 the dose has increased to 0.72 mSv.

From NM procedures the effective dose per caput had been 0.03 mSv from year 2000 to 2009 but has increased until 2018 to 0.04 mSv.

The uncertainties of collective effective doses consist of the uncertainties of frequencies and typical effective doses. The uncertainties of frequencies are based on the response rates (missing data) that are discussed in the paragraph 4.2. The uncertainties of frequency data from radiology departments including private clinics and nuclear medicine departments are 2–3% and 0.1%, respectively. A rough estimation of uncertainties of typical effective doses for plain radiography, contrast enhanced radiography, CT and interventional radiology are 10%, 50%, 30% and 50%, respectively. The estimation is based on the literature (EC 2008) and takes into account that especially in contrast enhanced examinations, CT and interventional radiology many of the typical mean doses are taken from literature. The estimated uncertainties of collective effective doses plain radiography, contrast enhanced radiography, CT and interventional radiology are 10%, 50%, 30% and 50%, respectively.

TABLE 13. The collective effective doses and per caput doses in Finland from all x-ray and NM examinations in 2008 and 2018 (Study I and IV).

Year	Collective effective dose from all x-ray examinations (manSv)	Collective effective dose from all NM examinations (CT included) (manSv)	Effective dose per caput from all x-ray examinations (mSv)	Effective dose per caput per all NM examinations (mSv)
2008 (x-ray)	2422		0.45	
2009 (NM)		186		0.03
2018	3948	215	0.72	0.04

The change of effective doses per caput from 2008 to 2018 for groups of x-ray procedures, and the relative contributions to the total effective doses per caput are shown in Table 14 (Study IV).

TABLE 14. The change of effective doses per caput in Finland from groups of x-ray procedures and contributions to the total effective dose per caput from x-ray procedures in years 2008 and 2018 (Study I and IV).

Effective dose per caput (mSv)				Contribution to total effective dose per caput from x-ray procedures (%)	
Group			**Change (%)**		
	2008	**2018**		**2008**	**2018**
Plain radiography*	0.073	0.082	12	16	11
Contrast enhanced radiography	0.055	0.038	-31	12	5
Computed tomography	0.26	0.50	91	58	70
Interventional radiology	0.063	0.098	57	14	14
Total	0.45	0.72	59	100	100

* Including dental examinations

The plain radiography includes dental intraoral, panorama and cephalometric radiographs. The dose per inhabitant from dental examinations in 2008 and 2018 was 0.003 mSv and 0.004 mSv, respectively.

The per caput effective doses for plain radiography, CT, fluoroscopy and interventional radiology from 2008 in European countries are compared in Figure 3 (Study II). The relative contributions are also illustrated in Figure 3 For x-ray procedures in EU countries and EFTA countries (except Liechtenstein) the collective effective dose is 547 500 manSv, resulting in a mean effective dose of 1.06 mSv per caput. For all European countries included in the survey the collective effective dose was 605 000 manSv, resulting in a mean effective dose of 1.05 mSv per caput.

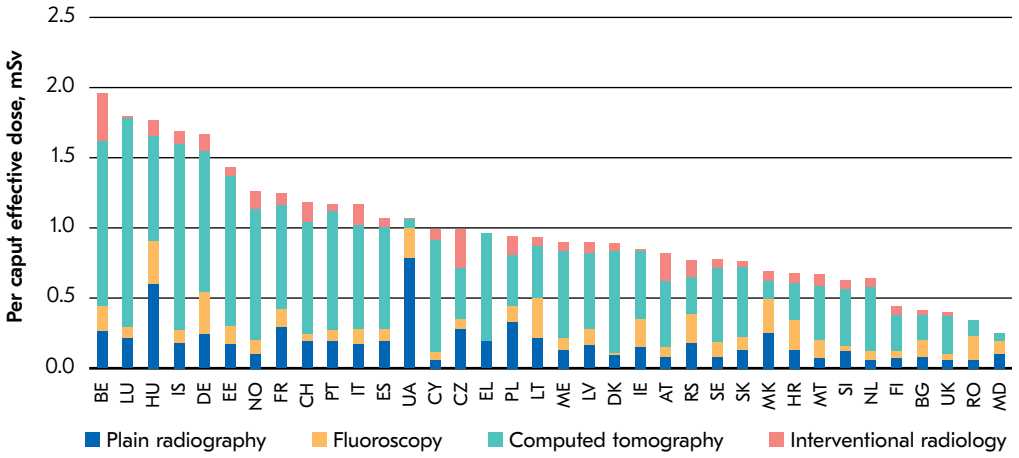

FIGURE 3. Per caput effective doses for different countries from x-ray procedures. For EL, data for the contributions of fluoroscopy and IR were not available. (Study II) (EC 2014b).

The increase of the total per caput effective dose in Finland is mainly caused by the increase of per caput effective doses of x-ray examinations among which the highest increase was of CT (91%) and interventional radiology (57%) (Study IV). The increase of per caput effective dose in plain radiography is minor (12%) while there is a considerable decrease of the per caput effective dose in contrast enhanced radiography (-31%). The collective effective dose from NM examinations increased 16%, but the influence on the total per caput effective dose decreased from 6% to 5%. The contribution of the main groups of x-ray procedures and NM procedures to the total collective effective dose for Finland in 2008/2009 (Study I), for Finland in 2018 (Study IV) and for 36 European countries including Finland (Study II) are shown in Figure 4.

The effective dose per caput from CT examinations has increased until 2018 to 0.50 mSv (Study IV). While in 1997 only 20% of the collective effective dose from x-ray procedures was from CT procedures, by 2018 its proportion has increased to 70%. The contribution of CT examinations to the total frequency doubled, while still remaining relatively low (17%) compared with their contribution to the total collective effective dose.

The total number of interventional procedures increased 67% during 2008–2018 (Table 4), while the number of PTCA procedures increased 59% (Study IV).

On the other hand, an effective dose per a PTCA procedure decreased from 24 to 17 mSv. The effective dose per caput from interventional procedures increased 57%. The contribution to the total collective effective dose remained the same during 2008–2018 (Figure 4) (Study I, II and IV).

Since 2005 to 2008 the effective dose per caput from plain radiography had decreased from 0.08 mSv to 0.07 mSv but was again increased in 2018 to 0.08 mSv (12%). Chest radiography and examinations of pelvis and hip contributed to the dose of this group 14% and 11%, respectively. Within plain radiography (excluding normal dental radiology) the proportion of the frequency of mammography examinations was only 13%, but the contribution to the collective effective dose of this group was 47% (Study IV).

The contributions of plain radiography, including normal dental radiology, and contrast enhanced radiology to the total collective effective dose decreased from 2008 to 2018, while the contribution of interventional radiology remained the same. Among these groups of x-ray procedures, the change was most remarkable for contrast enhance radiology (decrease from 12% to 5%). (Study IV)

Despite the slight decrease of the total number of NM examinations, the collective effective dose has been almost the same per inhabitant since 2000. The five most contributing procedures to the collective effective dose in 2018 are the same as shown in the Table 11. The collective effective dose from PET examinations is mainly due to the use of the ^{18}F radiopharmaceuticals. The use of ^{15}O has negligible influence on the collective effective dose. The contribution of the use of the ^{11}C radiopharmaceuticals to the collective effective dose from NM procedures is only 0.8%. The collective effective dose from CT in hybrid imaging has tripled between 2009 and 2018 from 23.7 manSv to 71.4 manSv (Study IV).

In 2012 and 2018, the mean effective dose for a Finn was 3.2 mSv and 5,9 mSv, respectively. The Finnish population is exposed to ionizing radiation from a number of sources, both natural and man-made. Two thirds of the collective effective dose is due to indoor radon. The total collective effective dose from radiological procedures contributed 15% and 13% in 2012 and 2018, respectively (Muikku et al. 2014, Siiskonen et al. 2020).

A comparison of contributions of the main groups of x-ray and NM procedures to the total collective effective dose for Finland and for 36 European countries is presented in Figure 4. The assessments of collective effective dose from radiological examinations for Finland in 2008/2009 (Study I) and in 2018 (Study IV) are based on the most accurate method and the assessment for 36

European countries including Finland (Study II) is based on Top20 -method. Underestimation of frequencies in Top 20 method has been compensated so that for countries which reported only Top 20 data, the results have been obtained from the results of the evaluation of frequencies with the Top 20 method, using a correction factor that takes into account the procedures not included in the Top 20. This correction factor has been taken as the average ratio between the overall total frequency and the total frequency evaluated by the Top 20 approach (total overall/total Top 20), calculated from the results for the 11 countries of the survey which reported both types of total frequencies. (Study II), (EC 2014b)

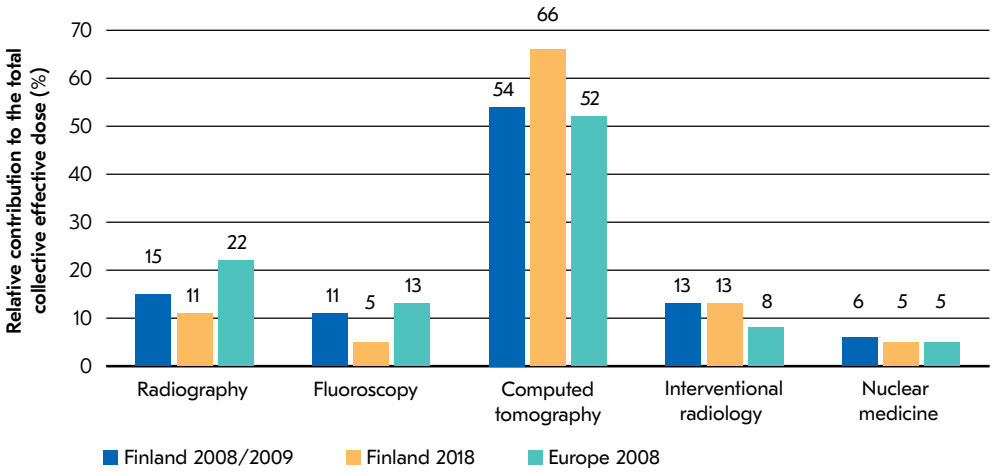

FIGURE 4. Contribution of the main groups of x-ray procedures and NM procedures to the total collective effective dose from radiological examinations for Finland in 2008/2009 (Study I), for Finland in 2018 (Study IV) and for 36 European countries including Finland (Study II).

5.5 Influence of the change of ICRP tissue weighting factors

Using the Top 20 method in grouping the examinations from plain radiography in 2008, the impact of the tissue weighting factors from ICRP 103 on collective effective dose is shown in Table 15 (Study I). The impact is the highest on the chest, breast and neck regions (increase 29–135%). The new tissue weighting factor by the ICRP for breast tissue has increased 58%. The decrease of the tissues weighting factors in the regions of pelvis and abdomen has decreased the proportional contribution from examinations of those anatomical areas of 10–18%. The biggest change (135%) is the increased influence of mammography examinations to the collective effective dose from plain radiography with a relative proportion of 31% (Study I).

TABLE 15. Collective effective doses in Finland from plain radiography in 2008 using Top 20 method with tissue weighting factors from ICRP 60 and ICRP 103 (Study I).

Top 20 no.	Procedure	Collective effective dose by ICRP 60 (manSv)	Collective effective dose by ICRP 103 (manSv)	Difference (%)
1	Chest	78.3	100.6	29
2	Cervical spine	8.2	16.5	100
3	Thoracic spine	13.0	13.7	5
4	Lumbal spine	114.4	101.7	-11
5	Mammography	62.9	147.9	135
6	Abdomen	40.6	36.5	-10
7	Pelvis and hip	76.7	63.2	-18
Total		394.1	480.0	22

The collective effective dose from CT procedures was 2744 manSv in 2018 when effective dose conversion coefficients from EU RP154 (EC 2008) based on ICRP 60 tissue weighting factors, were applied and 2728 manSv when new effective dose conversion factors, based on ICRP 103 tissue weighting factors, were applied (Study IV). The difference is only 0.6%. The differences between the two sets of conversion factors are shown in Table 16.

TABLE 16. Comparison between conversion factors (mSv/mGy cm) for CT (Study IV).

Body region	EC RP 154, ICRP 60 (2008)	Deak et al., ICRP 103 (2010)	Difference (%)
Head	0.0021	0.0019	-9.5
Neck	0.0059	0.0052	-12
Chest	0.014	0.0146	4.3
Abdomen	0.015	0.0153	2.0
Pelvis	0.015	0.0129	-14
Trunk	0.015	not given	

6 Discussion

6.1 Explanatory factors

In total the frequencies of x-ray procedures per 1000 population excluding dental examinations decreased 9% during 2008–2018 (Table 4), however the effective dose per caput increased 59% (Table 14) (Study IV). The total change of frequencies of NM procedures per 1000 population decreased 5% (Table 6), however the effective dose per caput increased 33% (Table 13) (Study IV). The main reason for higher per caput doses in total is the increased use of CT, however there are also other explaining factors that are discussed in following paragraphs for each group of procedures.

6.1.1 Plain radiography

The frequency of plain radiography excluding dental examinations decreased 18% in total during 2008–2018 (Table 4), however the mean effective dose per inhabitant increased slightly (12%). The contribution to the total effective dose per inhabitant from x-ray examinations decreased only 5% (Table 14). (Study IV)

The frequency of dental examinations decreased 3% (Table 5), however the frequency of panorama examinations increased 21%. In the estimation of the collective effective dose, dental examinations are included in the main group plain radiography. The dose per inhabitant from dental examinations was in 2008 and 2018 only 0.003 mSv and 0.004 mSv, respectively. While the frequency of dental examinations is very high their contribution to the population dose from plain radiography stayed unchanged in only 4% (Study I, IV).

The frequencies of radiography examinations of the head and neck and abdomen decreased 61% and 70% respectively, while that of the chest, pelvis and hip did not change substantially during 2008–2018 (Study IV). One reason for the changes in frequencies is the development of CT techniques and the increased frequencies are discussed in paragraph 6.1.2.1. A clear increase (26%) can be seen in the frequency of mammography examinations due to changes in the regulation

from the beginning of 2007 that widened the screening age from 50–59 to 50–69 years gradually by the end of year 2016. Moreover, the mean effective dose from mammography was more than doubled due to the new tissue weighting factor for breast, which is discussed below. The increased collective effective dose from mammography due to increased frequency and increased mean effective dose influenced remarkably to the increase of the collective effective dose from the plain radiography (Study IV).

The main reason for the almost unchanged collective effective dose from plain radiography was the use of new conversion factors from ICRP 103 that increases the collective effective dose by about 22% (Table 15), i.e. the decrease of collective dose caused by the decreased frequencies was compensated by the increase of collective dose due to using the new tissue weighting factors in the calculation of effective dose per procedure (Study I and IV).

6.1.2 Computed tomography

6.1.2.1 CT in radiology

Frequencies of CT examinations of the head and neck, chest, abdomen, pelvis and hip and trunk increased 49, 44, 95, 17 and 180%, respectively, and collective effective doses from CT examinations increased 1, 60, 99, 33 and 147%, respectively. The increase of the frequencies of CT examinations explains mostly the increase of the collective effective dose. (Study IV)

While there is a great increase of the frequencies of CT examinations, it is noted that frequencies of plain radiography have decreased. For example, while the frequency of CT of head without contrast media increased 52% during 2008–2018, the frequency of skull radiography decreased 74%. Correspondingly, the frequency of CT abdomen without contrast media tripled and the frequency of abdomen radiography decreased almost to one third. (Rantanen et al. 2009, Pastila et al. 2019)

The development of CT equipment was remarkable during 2008–2018. While in 2008 there was wide range of 1–16 slice devices, in 2018 most of the CT equipment were 64 slice devices. The *KLP* values of most common procedures in 2008 were based on STUK measurements in the standard phantoms (Karppinen and Järvinen 2006), but in 2018 updated *KLP* values were based on data collection of patient examinations (Lajunen 2015). For example, in 2008 the *KLP* value for CT head varied from 650 mGy cm with a 1-slice device to 810 mGy cm with a 16-slice device,

but in 2018 the mean value was 672 mGy cm for all devices (Table 8). The overall tendency was that the *KLP* values decreased and correspondigly, the diagnostic reference levels (DRLs) for particular body regions decreased about 20% in 2007–2013 (Lajunen 2015). Moreover, the availability of more detailed data of *KLP*s improved the preciseness of the estimated collective effective dose from CT examinations.

The change from ICRP 60 tissue weighting factors to the ones based on ICRP 103 contributed to the increased collective effective dose from CT examinations only 0.6%, while the differences between conversion factors were up to -14% on head, neck and pelvis regions and up to 4.3% on chest and abdomen regions (Table 12) (Study IV). The influence of tissue weighting factors has been notable on each anatomical region, but together with the changes in frequencies the contribution of frequencies had more prominent influence.

6.1.2.2 Radiotherapy CT simulations

There was a large amount of variation in the exposure parameters used for CT simulations at radiotherapy departments (Study III). Exposure parameters are often selected based on the default settings recommended by the manufacturer. Additional and continuous optimization is typically not performed for these CT systems. It should be kept in mind that some of these parameters not only affected patient exposure but also image quality, which should not be spoiled by non-optimal exposure parameters. Surprisingly, tube voltages other than 120 kV were used in some places. Slice thickness was 2.5 mm or below in all cases, and this complies with recommendation of 3 mm (IAEA 2012). Pitch values of 1 were generally used, contrary to the recommendation of Liu et al. (Liu et al. 2008). However, the pitch values used do not comply with the values of 1.5–2 recommended by IAEA (IAEA 2012) either. It also seems that the dose level is not adjusted in relation to the pitch or slice thickness, and this might even increase the possible differences in image quality.

As expected, the largest variation in scan length can be seen in head and neck simulation, where there was the largest variation in target volumes. For other targets, anatomical range of the target is more fixed. However, the anatomical scan range is typically selected locally for different targets, and the largest variation is between hospitals. Dose levels are also generally higher than those used in diagnostics. Only 23% of the calculated average doses would comply with the established national DRLs, whereas 34% of values were over 2-fold higher

than the DRL. The results are comparable with the results of Garcia-Ramirezet al. (Garcia-Ramirezet et al. 2002) reported dose levels of 1–2 cGy higher when large bore CT was compared with normal diagnostic CT. (Study III)

6.1.3 Contrast enhanced examinations

Frequencies of contrast enhanced examinations decreased a total of 22% during 2008–2018 (Study IV). The major contribution to the collective effective dose arises from CA procedures. The number of CA procedures increased 46% during 2008–2018, but an average effective dose per the CA procedure decreased from 6 to 3 mSv (Study IV). Therefore, the considerably lower dose per procedure caused a decrease of the collective effective dose despite the increase of the frequency. The reasons for lower doses per procedure are similar to those discussed in the paragraph 6.1.4.

The frequency of other contrast enhanced examinations decreased. For example, a code for barium meal has been removed, because in 2011 there were only 20 examinations. Moreover, according to the European guidelines (EC 2008) barium enema is among the most important procedures in estimating collective effective dose, because the mean effective dose is relatively high (Table 9), but in Finland the frequency of that procedure is very low (181 examinations in 2018) (Pastila et al. 2019). However, there are still relatively frequent examinations like barium follow and endoscopic retrograd cholangiopancreaticography of about 2500 examinations per each.

It was noticed that while there is decrease of some contrast enhanced examinations, simultaneously there is increase in some CT examinations. For example, there was a remarkable decrease of intravenous urography (IVU) examinations in 2008–2018 and only 53 examinations were carried out in 2018, but CT urography was established and there were 448 examinations in 2018 (Rantanen et al. 2009; Pastila et al. 2019).

6.1.4 Interventional radiology

The frequency of interventional procedures increased 67% during 2008–2018 (Table 4) (Study IV). The major contribution to the collective effective dose arises from PTCA procedures. The frequency of PTCA procedures increased 59%. Another notable procedure is blockage of nerve root with CT guidance, which

had only 4% and 3% share of the total frequency in the group in 2008 and 2018, respectively (Rantanen et al. 2009, Pastila et al. 2019).

On the other hand, a mean effective dose per a PTCA procedure decreased from 24 to 17 mSv (Study IV), which is now closer to the European average of 36 countries (15 mSv) (EC 2014b). The new technology enables the use of pulsing beams that decrease the dose, and additionally other techniques for optimization have been promoted extensively by STUK, such as selecting a wrist instead of groin route, using an appropriate imaging protocol to avoid unnecessary exposures, lifting the table as close to the imaging receptor as convenient in order to increase x-ray tube distance from the patient skin, selecting projections that decrease patient exposures, minimizing the use of magnification, delineation of the radiation field and decreasing low energy scattered radiation by adjusting radiation quality (Järvinen et al. 2018).

The main reason for the increase of the collective effective dose from interventional procedures arises from increased frequency of PTCA procedures (Study IV). However, the increase of the collective effective dose could be much more without continuous optimization of radiation protection.

6.1.5 Nuclear medicine

The frequency of all NM examinations in Finland has been very low compared to other European countries (Figure 2) (Study II). The frequency of PET examinations has increased and especially the use of ^{18}F radiopharmaceuticals (Study IV). The collective effective dose from PET examinations is mainly due to the use of the ^{18}F radiopharmaceuticals (Study I and IV).

The use of CT in NM imaging increased remarkably in 2009–2018 (Study IV). Hybrid imaging with CT has doubled the mean effective doses per procedure compared to traditional NM examinations. While a typical mean effective dose from CT was 2–4 mSv, a mean effective dose from CT in a whole body PET-CT was up to 10.6 mSv (Table 11) (Study IV). The low-dose CT attenuation correction is used mainly in cardiovascular procedures and in those the mean effective dose from CT was minimal (Study I and IV).

The mean effective dose per caput has been almost the same in Finland since 2000. The increased use of hybrid imaging (SPECT-CT and PET-CT) has slightly increased the mean effective dose per individual during 2009–2018 from 0.03 to

0.04 mSv (Study I and IV). The main reason for the low result compared to other European countries is the low frequency of NM examinations (Study II).

6.2 Comparison of results with other countries

6.2.1 Diagnostic procedure

In the survey of 36 European countries (Study II), the average collective effective dose per caput was 1.1 mSv, and in the USA in 2016 (NCRP 2019) it was 2.16 mSv. In Finland the mean effective dose per individual has increased to 0.76 mSv but is still on the reasonable level compared to the above-mentioned examples. In the USA in 2016, the per caput effective dose from CT examinations was 1.37 mSv, and the number of CT examinations had increased in 10-year period 20%; in Finland in 2018 the per caput dose from CT examinations was only 0.50 mSv despite the considerable increase (81%) of the frequency of CT examinations (Study IV).

The overall per caput effective dose in Finland in 2008 was about half the value of per caput effective dose estimated in Australia (Hayton et al. 2013) and about one-third of the corresponding value in the USA (NCRP 2019) (Study II). In the USA the trend has been slightly decreasing (NCRP 2019). Relative distributions in Australia and USA (Figure 5) show that CT is dominating and the development in USA shows even increasing proportion for CT of the collective effective dose. The development has been similar in Finland.

Since year 1997 to 2008 the collective effective dose from x-ray procedures has been unchanged in Finland, although the contribution of different categories of procedures has varied (Study I). Compared to the trend of increased doses reported by UNSCEAR (UNSCEAR 2008) this is exceptional. Among 36 European countries, the per caput effective dose from x-ray examinations in Finland is fifth lowest (Figure 3) (Study II). One reason for these results may be due to the awareness of patient doses and optimization. STUK has actively disseminated information on optimization of x-ray procedures on regular onsite inspections and workshops. A special emphasis has been given to CT.

The importance of age/sex distributions was also reviewed (Study II). Based on EUROSTAT data, the overall age distribution of the EU 27 countries shows no significant differences between the data from 2005 and 2010. Comparisons of the average data on age/sex distribution for the five DDM 1 countries and four

DDM 2 countries, for specific x-ray examinations, indicated that the distributions are sufficiently similar to conclude that the usage of the European average distributions (EC 2008) is still reasonable when specific national data on age and sex distribution per examination are not available (Study II). Based on Danish data from 2004 (EC 2008) it can be estimated that elderly people had most of the x-ray procedures, for whom the lifetime risks of radiation-induced cancer are much reduced compared to general population.

Although a relatively low value of population dose can be a good sign for the successful implementation of the justification and optimization principles in radiation protection, it could also be attributed to the lack of imaging resources. On the other hand, a relatively high value should imply considerations on whether the justification and optimization principles are properly implemented. (Study II)

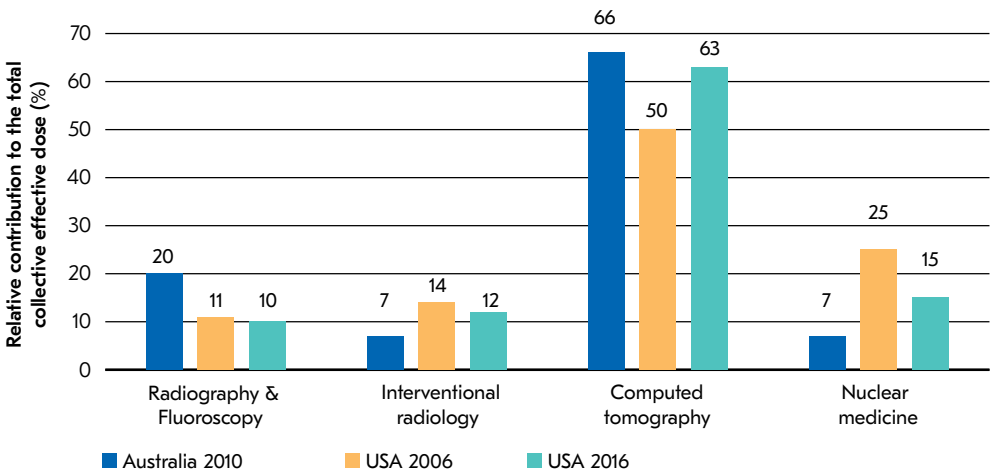

FIGURE 5. Relative contribution of the main groups of x-ray examinations and NM examinations to the total collective effective dose for Australia in 2010 (Hayton et al. 2013) and for USA in 2006 and 2016 (NCRP 2019).

The level of implementation of two main radiation protection principles, justification and optimization, should be assessed continuously to be able to focus resources and efforts efficiently to improve radiation protection. One tool for the assessment is to compare development of frequencies of examinations and exposure levels of patients nationally and internationally.

Comparing the results in the Study II with an earlier estimation of population dose in Europe, in the DDM1 countries (EC 2008), there seems to be a trend upwards; however, because for part of the DDM1 countries the new data was based on Top 20 estimations only, no strict conclusion about the percentage increase could be made. While the average dose in Europe turned out to be relatively low, there are high variations of the results between countries (Study II).

6.2.2 Radiotherapy CT simulations

The justification for the higher dose levels in radiotherapy CT simulations compared to diagnostic imaging was questioned by the radiation protection authority in the annual meeting with radiation therapy physicists. Some of the CT simulators with the lowest dose levels in simulations are also used for diagnostic imaging and, therefore, their dose levels are probably more optimized. Moreover, the survey results show that, for each simulated target area, there was at least one hospital using dose levels that do not exceed the corresponding DRLs (Study III). However, these hospitals were still satisfied with the image quality. A national recommendation was given to optimize dose levels. In the survey of the Study III, there were a limited number of devices from each manufacturer, and therefore, a comparison between different manufacturers' CT dose levels cannot be carried out, because it would also reveal the dose levels of individual hospitals. However, it can be concluded that there was no direct correspondence between a dose level and CT device's type. Dose levels were collected as they were displayed by the system, and this adds some additional uncertainty to the results. National acceptability criterion for the uncertainty of dose display is 25%. However, some of the oldest Toshiba (nowadays Canon) systems might still give $CTDI_{vol}$ values, which are based on the maximum tube current instead of the average value. This might distort some of the results from Toshiba systems. CT simulation is only one part of the diagnostic and therapy process; therefore, other related exposures should also be evaluated, such as imaging for treatment verification purposes. (Study III)

6.3 Recent and future developments

Recently manufacturers have provided dose monitoring systems (DMS) (also called dose management systems) especially for CT and interventional radiology. A DMS may be dedicated to facilitating data collection and processing, statistical comparisons, reporting and management of radiation dose related information that allow comprehensive estimates of patient (Fitousi 2017, Tsalafoutas et al. 2020). The use of these systems might provide data for national dose registers. Moreover, there are emerging developments of artificial intelligence based methods, such as deep learning, for assessing patient doses. This methodology has been demonstrated for CT using automatic organ segmentation and MC calculations, but also for dosimetry in molecular imaging and radiotherapy (Maier et al. 2018, Peng et al. 2020, Arabi and Zaidi 2020).

It seems that in future more computational methods will be used to assess patient doses and that will contribute on a local level for optimizing patient protection. On regional and national levels, improved availability of clinical data and data management would contribute to assessment of collective effective doses..

7 Conclusions

In Finland the total collective effective dose from x-ray and NM procedures has increased 59% in 2008–2018, mainly due to the increase of collective effective doses from CT and interventional radiology. The collective effective dose from NM examinations is only 5% of the total collective dose from all radiological examinations. (Study I and IV)

About 70% of the collective effective dose from x-ray examinations was caused by CT in 2018, while the proportion of CT procedures was only 16.5%. It is concluded that CT procedures are the major and increasing source of the collective dose from x-ray procedures. While the use of new tissue weighting factors (ICRP 103) increases the population dose from plain radiography, it has minimal effect on the population dose from CT examinations. (Study IV)

There was a large amount of variation in the dose levels and exposure parameters used for radiotherapy CT simulations. Patient exposure levels were generally much higher than those used for diagnostics. Exposure parameters should be reviewed and optimized together with the dose level also for radiotherapy CT simulations. (Study III)

In comparison with 36 European countries is was shown that frequencies of both x-ray and NM examinations were less that in average in Europe (Study II). This indicates that the level of justification is at least at the average European level. The comparison of per caput effective doses showed that the dose in Finland was on the lowest quarter among European countries (Study II). Despite of the increased collective effective dose from x-ray and NM examinations, the overall per caput effective dose in Finland in 2018 was still well below the average of European countries in 2008 and only a third of the per caput effective dose in USA in 2016 (Study IV). This indicates that both justification and optimization of examinations is at a good European level.

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References

AAPM Report No. 96. The measurement, reporting, and management of radiation dose in CT. American Association of Physicists in Medicine; 2008.

AAPM Report No. 204. Size-specific dose estimates (SSDE) in pediatric and adult body CT examinations. American Association of Physicists in Medicine; 2011.

Arabi H, Zaidi H. Applications of artificial intelligence and deep learning in molecular imaging and radiotherapy. Eur J Hybrid Imaging 4 (17); 2020. https://doi.org/10.1186/s41824-020-00086-8

Bly R, Järvinen H, Korpela H, Tenkanen-Rautakoski P, Mäkinen A. Estimated collective effective dose to the population from X-ray and nuclear medicine examinations in Finland. Radiation Protection Dosimetry 147 (1-2): 233–236; 2011.

Bly R, Jahnen A, Järvinen H, Olerud H and Vassileva J. Collective effective dose in Europe from X-ray and nuclear medicine procedures. Radiation Protection Dosimetry 165 (1–4): 129-132; 2015.

Bly R, Järvinen H, Kaijaluoto S, Ruonala, V. Contemporary collective effective dose to the population from x-ray and nuclear medicine examinations – changes over last 10 years in Finland. Radiation Protection Dosimetry 189 (3): 318–322; 2020.

Christner JA, Kofler JM, McCollough CH. Estimating effective dose for CT using dose-length product compared with using organ doses: consequences of adopting International Commission on Radiological Protection publication 103 or dual-energy scanning. Am. J. Roentgenol. 194 (5): 1404; 2010.

Dance, DR. Monte Carlo calculation of conversion factors for the estimation of mean glandular breast dose. Phys. Med. Biol. 35 (9): 1211–1219; 1990.

Dance DR, Skinner CL, Young KC, Beckett JR, Kotre CJ. Additional factors for the estimation of mean glandular breast dose using the UK mammography dosimetry protocol. Phys. Med. Biol. 45 (11): 3225; 2000.

Deak PD, Smal Y, Kalender WA. Multisection CT protocols: Sex- and age-specific conversion factors used to determine effective dose from dose-length product. Radiology 257: 158–166; 2010.

Drexler G, Panzer W, Widenmann L, Williams G, Zankl M. The calculation of dose from external photon exposures using reference human phantoms and Monte Carlo methods, Part III: Organ doses in x-ray diagnosis. GSF-Bericht 11/90. Neuherberg: GSF; 1990.

European Commission. Council Directive 97/43 Euratom of 30 June 1997 on health protection of individuals against the dangers of ionizing radiation in relation to medical exposure; 1997.

European Commission. European guidance on estimating population doses from medical X-ray procedures. Radiation Protection 154 (RP 154). Luxembourg: Publications Office of the European Union; 2008.

European Commission. Council Directive 2013/59/Euratom of 5 December 2013, laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom. Official Journal of the European Communities No L 13, Volume 57; 2014a.

European Commisson. Medical Radiation Exposure of the European Population. Part 1/2. Radiation Protection No 180; 2014b. Available from https://ec.europa.eu/energy/sites/ener/files/documents/RP180.pdf

Fitousi N. Patient dose monitoring systems: A new way of managing patient dose and quality in the radiology department. Phys Med 44: 212–221; 2017.

Food and Drug Administration. CDRH Organ Dose Handbooks 85-8239, 89-8031, 92-8282, 95-8288 and 95-8289. Available from https://www.fda.gov/radiation-emitting-products/medical-x-ray-imaging/cdrh-organ-dose-handbooks

Garcia-Ramirez JL, Mutic S, Dempsey JF, Low DA, Purdy JA. Performance evaluation of an 85-cm-bore x-ray computed tomography scanner designed for radiation oncology and comparison with current diagnostic CT scanners. Int. J. Radiat. Oncol. Biol. Phys. 54 (4): 1123–1131; 2002.

Hart D, Jones DG, Wall BF. Estimation of effective dose in diagnostic radiology from entrance surface dose and dose-area product measurements. National Radiological Protection Board (NRPB), Report NRPB-R-262 and related software report NRPB-SR262; 1994.

Hart D and Wall BF. Radiation Exposure of the UK Population from Medical and Dental X-ray Examinations. Report NRPB-W4. National Radiological Protection Board (NRPB); 2002.

Hayton A, Wallace A, Marks P, Edmonds K, Tingey D, Johnston P. Australian per caput dose from diagnostic imaging and nuclear medicine. Radiat. Prot. Dosim. 156 (4): 445–450; 2013.

Huda W, Tipnis S, Sterzik A, Schoepf UJ. Computing effective dose in cardiac CT. Phys. Med. Biol 55 (13): 3675–84; 2010.

Huda W, Magill D, He W. CT effective dose per dose length product using ICRP 103 weighting factors. Med Phys 38 (3): 1261–1265; 2011.

International Atomic Energy Agency (IAEA). Fundamental Safety Principles; Safety Fundamentals. IAEA; 2006.

International Atomic Energy Agency (IAEA) Technical Report Series No. 457 Dosimetry in Diagnostic Radiology: An International Code of Practice. IAEA; 2007.

International Atomic Energy Agency (IAEA). Quality Assurance Programme for Computed Tomography: Diagnostic and Therapy Applications. IAEA Human Health Series No. 19. IAEA; 2012.

International Atomic Energy Agency (IAEA). Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards; General Safety Requirements Part 3. IAEA; 2014.

ICRP Publication 53. Radiation dose to patients from radiopharmaceuticals. Ann ICRP 18 (1–4); 1988.

ICRP Publication 60. 1990 Recommendations of the International Commission on Radiological Protection. Ann ICRP 21 (1–3); 1991.

ICRP Publication 80. Radiation dose to patients from radiopharmaceuticals – Addendum 3 to ICRP Publication 53. Annals of the ICRP 28 (3); 1998.

ICRP Publication 89. Basic anatomical and physiological data for use in radiological protection reference values. Annals of the ICRP Vol. 32 (3-4); 2002.

ICRP Publication 102. Managing patient dose in multi-detector computed tomography (MDCT). Annals of the ICRP Vol. 37 (1); 2007a.

ICRP Publication 103. The 2007 recommendations of the International Commission on Radiological Protection. Annals of the ICRP 37 (2–4); 2007b.

ICRP Publication 106. The 2007 radiation dose to patients from radiopharmaceuticals – Addendum 3 to ICRP Publication 53. Annals of the ICRP 38 (1–2); 2008.

ICRP Publication 110. Adult reference computational phantoms. Annals of the ICRP 39 (2); 2009.

ICRP Publication 128. Radiation dose to patients from radiopharmaceuticals: A compendium of current information related to frequently used substances. Annals of the ICRP 44 (2S); 2015.

ICRP Publication 74. Conversion Coefficients for use in Radiological Protection against External Radiation. Annals of the ICRP 26 (3–4);1996.

Fitousi N. Patient dose monitoring systems: A new way of managing patient dose and quality in the radiology department. Phys Med 44: 212–221; 2017.

Food and Drug Administration (FDA), U.S. Department of Health. CDRH organ dose handbooks 85-8239, 89-8031, 92-8282, 95-8288 and 95-8289. Available from https://www.fda.gov/radiation-emitting-products/medical-x-ray-imaging/cdrh-organ-dose-handbooks

IEC International Standard 60580:2019. Medical electrical equipment – Dose area product meters. IEC; 2019.

IEC International Standard 60601-2-44:2009. Amendment 1 Medical electrical equipment. IEC; 2012. Part 2–44 Particular requirements for the safety of X-ray equipment for computed tomography. IEC; 2016.

Jansen JT, Dierker J and Zotelief J. Calculation of air-kerma to kverage glandular dose conversion factors for mammography units employing various target-filter combinations Proc. 10th Sci. Symp. of the Belgian Society of Hospital Physicists, ed. Schanken B and Vanregemorter J (Antwerp: BVZF/SBPH): 67–76; 1994.

Jansen JT, Shrimpton PC. Development of Monte Carlo simulations to provide scanner-specific organ dose coefficients for contemporary CT. Phys. Med. Biol. 61 (14): 5356–77; 2016.

Jones DG, Shrimpton PC. Survey of CT practice in the UK: Part 3. Normalised organ doses calculated using Monte Carlo techniques. Chilton, NRPB-R250 and related software NRPB-RS250; 1991.

Järvinen H. Terveydenhuollon säteilyn käytöstä (röntgendiagnostiikka ja toimenpideradiologia) väestölle aiheutuvan säteilyannoksen määrittäminen (Determination of the collective effective dose to population from the medical use of radiation (x-ray examinations and interventional procedures)) STUK-TR 21. Helsinki: STUK – Radiation and Nuclear Safety Authority; 2016. (In Finnish)

Järvinen H. (ed.), Eskola M, Hallinen E, Järvinen J, Kivelä A, Mäkelä T, Parviainen T, Pirinen M, Rissanen T, Sierpowska J, Siiskonen T, Vinni-Lappalainen K. Säteilyn käytön turvallisuus kardiologiassa (Radiation safety in cardiology). STUK Advice 09/2018. Helsinki: STUK – Radiation and Nuclear Safety Authority; 2018. (In Finnish)

Kaijaluoto S (ed.), Korpela H, Bly R, Toroi P. Isotooppitutkimukset ja -hoidot Suomessa 2012 (Nuclear medicine examinations and therapeutic treatments in Finland in 2012). STUK-B 169. Helsinki: STUK–Radiation and Nuclear Safety Authority; 2014. (In Finnish)

Kaijaluoto S, Liukkonen J. Isotooppitutkimukset ja -hoidot Suomessa vuonna 2018, terveydenhuollon valvontaraportti (Nuclear medicine examinations and therapeutic treatments in Finland in 2018, supervision report in health care). STUK-B 252. Helsinki: STUK – Radiation and Nuclear Safety Authority; 2020. (In Finnish)

Kalender WA, Schmidt B, Zankl M, Schmidt M. A PC program for estimating organ dose and effective dose values in computed tomography. Eur. Radiol. 9: 555–562; 1999.

Kalender WA. CTDI and patient dose: a European perspective 54th Annu. Meeting of the AAPM. Med. Phys. 39: 3906; 2012.

Kalender WA. Dose in X-ray computed tomography. Phys. Med. Biol. 59: R129–R150; 2014.

Karppinen J, Järvinen H. Tietokonetomografialaitteiden käytön optimointi (Optimization of computed tomography equipments). STUK-A220. Helsinki: STUK–Radiation and Nuclear Safety Authority; 2006. (In Finnish)

Kelaranta A, Toroi P, Vock P. Incident air kerma to absorbed organ dose conversion factors for breast and lung in PA thorax radiography: The effect of patient thickness and radiation quality. Physica Medica 32: 1594–1601; 2016.

Kuntaliitto (Association of Finnish Local and Regional Authorities). Radiologinen tutkimus- ja toimenpideluokitus (Classification of radiological examinations and procedures). Helsinki: Kuntaliitto; 2018. (In Finnish)

Lajunen A. Indication-based diagnostic reference levels for adult CT-examinations in Finland. Radiation Protection Dosimetry 165 (1–4): 95–97; 2015.

Liu RR., Prado KL, Cody D. Optimal acquisition parameter selection for CT simulators in radiation oncology. J. Appl. Clin. Med. phys 9 (4): 2762–2792; 2008.

Maier J, Eulig E, Dorn S, Sawall S and Kachelrieß M. Real-time patient-specific CT dose estimation using a deep convolutional neural network. IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC); 2018. https://doi.org/10.1109/NSSMIC.2018.8824626

McParland BJ. A study of patient radiation doses in interventional radiological procedures. The British Journal of Radiology 71 (842): 175–185; 1998.

Merimaa K, Järvinen H, Kortesniemi M, Karppinen J. A direct method for air kerma-length product measurement in CT for verification of dose display calibrations. Radiation Protection Dosimetry;140 (3): 274–280; 2010.

Ministry of Social Affairs and Health. Decree on the medical use of radiation (423/2000).

Muikku M, Bly R, Lahtinen J, Lehtinen M, Siiskonen T, Turtiainen T, Valmari T, Vesterbacka K. Suomalaisten keskimääräinen efektiivinen annos; Annoskakku 2012 (The mean effective dose for Finns – Review 2012). STUK-A259. Helsinki: STUK –Radiation and Nuclear Safety Authority; 2014. (In Finnish)

NCRP Report. Medical radiation exposure of patients in the United States (2019). Report No. 184; 2019.

Pastila R (ed.). Radiation Practices; Annual Report 2018. STUK-B 239. Helsinki: STUK–Radiation and Nuclear Safety Authority; 2019.

Peng Z, Fang X, Yan P, Shan H, Liu T, Pei X, Wang G, Liu B, Kalra MK and Xu XG. A method of rapid quantification of patient-specific organ doses for CT using deep-learning-based multi-organ segmentation and GPU-accelerated Monte Carlo dose computing. Med Phys. 47 (6): 2526–2536; 2020.

Radiation Act (859/2018).

Rantanen E (ed.). Radiation Practices; Annual Report 2008. STUK-B 107. Helsinki: STUK–Radiation and Nuclear Safety Authority; 2009.

Ruonala V. Radiologisten tutkimusten ja toimenpiteiden määrät vuonna 2018 (Number of radiological examinations in Finland in 2019). STUK-B242. Helsinki: STUK–Radiation and Nuclear Safety Authority; 2019. (In Finnish)

Shrimpton PC, Jones DG. Normalised organ doses for x-ray computed tomography calculated using Monte Carlo Techniques and a Mathematical Anthropomorphic Phantom. Radiation Protection Dosimetry 49, (1-3): 241–243; 1993.

Shrimpton PC, Hiller MC, Lewis MA, Dunn M. Doses from computed tomography examinations in the UK – 2003 Review. NRPB-W67. Chilton: National Radiological Protection Board; 2005.

Siiskonen T (ed.), Bly R, Isaksson R, Kaijaluoto S, Kiuru A, Kojo K, Kurttio P, Lahtinen J, Lehtinen M, Muikku M, Peltonen T, Ruonala V, Torvela T, Turtiainen T, Virtanen S. Suomalaisten keskimääräinen efektiivinen annos vuonna 2018 (The mean effective dose for Finns – Review 2018). STUK-A 263. Helsinki: STUK–Radiation and Nuclear Safety Authority; 2020. (In Finnish)

Stamm G, Nagel H. CT-Expo — A novel program for dose evaluation in CT RöFo - Fortschritte auf dem Gebiet der R (ROFO-FORTSCHR RONTG) 174 (12): 1570–6; 2003.

STUK tiedottaa 1/2004. Röntgentutkimuksesta potilaalle aiheutuvan säteilyaltistuksen määrittäminen (Determining the patient's exposure to radiation in x-ray examinations).
Helsinki: STUK–Radiation and Nuclear Safety Authority; 2004. (In Finnish)

Tapiovaara M, Lakkisto M and Servomaa A. PCXMC: A PC-based Monte Carlo program for calculating patient doses in medical x-ray examinations. STUK-A139.
Helsinki: STUK–Radiation and Nuclear Safety Authority; 1997.

Tapiovaara M, Siiskonen T. PCXMC 2.0 User's Guide. STUK TR-7.
Helsinki: STUK–Radiation and Nuclear Safety Authority; 2008.

Tenkanen-Rautakoski Petra (toim.). Radiologisten tutkimusten ja toimenpiteiden määrät vuonna 2008 (Number of radiological examinations in Finland in 2008).
STUK-B 121. Helsinki: STUK–Radiation and Nuclear Safety Authority; 2010.
(In Finnish)

Toroi P, Kaijaluoto S, Bly R. Patient exposure levels in radiotherapy CT simulations in Finland. Radiation Protection Dosimetry; 167 (4): 602–607; 2015.

Tsalafoutas IA, Kharita MH, Al-Naemi H, Kalra MK. Radiation dose monitoring in computed tomography: Status, options and limitations. Phys Med 79: 1–15; 2020.

UNSCEAR 2008. Sources and effects of ionizing radiation; United Nations Scientific Committee on the effects of atomic radiation.
UNSCEAR 2008 Report to the General Assembly, with scientific annexes.
Volume I: SOURCES. Annex A, Medical exposure.

World Health Organization. Efficacy and Radiation Safety in Interventional Radiology. Chapter 4. Geneva: WHO; 2000.

Wu X, Gingold EL, Barnes GT, Tucker DM. Normalized average glandular dose in molybdenum target-rhodium filter and rhodium target-rhodium filter mammography. Radiology 193 (1): 83–89; 1994.

Zankl M, Panzer W, Drexler G. The calculation of dose from external photon exposures using reference human phantoms and Monte Carlo methods. Part VI: Organ doses from computed tomographic examinations. GSF-Bericht 30/91. Neuherberg: GSF; 1991.

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ESTIMATED COLLECTIVE EFFECTIVE DOSE TO THE POPULATION FROM X-RAY AND NUCLEAR MEDICINE EXAMINATIONS IN FINLAND

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The collective effective doses to the population from X-ray and nuclear medicine (NM) examinations in Finland in 2008 and 2009, respectively, were estimated. The estimated collective effective dose per inhabitant was 0.45 mSv from X-ray examinations and 0.03 mSv from NM examinations. The collective effective doses per inhabitant have not changed substantially during the last 10 y. However, proportional dose due to CT examinations has increased from 50 % in 2005 to 58 % in 2009 of the total collective effective dose from all X-ray examinations and proportional dose of PET examinations from 7 to 13 % of the total collective effective dose from NM examinations. The collective effective dose from conventional plain radiography was over 20 % higher when estimated using the new (ICRP 103) tissue weighting factors than that obtained using the old (ICRP 60) tissue weighting factors.

INTRODUCTION

European Council (EC) Directive (Medical Exposure Directive, MED)[1] defines the legal requirements for radiation protection of individuals submitted to medical exposures in the European Union. According to Article 12 the Member States shall ensure that the distribution of individual dose estimates from medical exposure is determined for the population and for relevant reference groups of the population.

In 2008 EC published practical guidance on estimating population doses from medical X-ray procedures (RP 154)[2]. Based on the guidance population dose can be estimated taking into account all possible procedures in the country or using a limited number of procedures that have the biggest influence on population dose. The Top 20 method takes into account totally only 20 procedures covering radiography, fluoroscopy, angiography, computed tomography (CT) and interventional radiology.

In Finland the collective effective doses to the population from X-ray and nuclear medicine (NM) examinations have been estimated regularly in few years periods over 10 y.

METHODS

Collection of frequencies of procedures

The frequencies of examinations were collected by questionnaires sent to all X-ray and NM units in Finland from 2008 and 2009, respectively. The response rates were 97 and 100 %, respectively. Radiological procedures are classified in Finland using a national coding system[3] with more than 800 codes. For some procedures there are three different codes depending on the complexity of the procedure.

Effective doses from radiodiagnostic procedures

The average effective doses for plain radiography were calculated using PCXMC programme[4]. Data from totally 1000 examinations were collected in 2006 from randomly selected 35 hospitals. In contrast enhanced radiography and in interventional radiology, the average effective doses are based on typical dose area product (DAP) values or in few cases effective doses from the literature[5–9]. For the conversion from DAP values to the effective dose conversion factors were taken from the literature[5, 6]. For PTCA and CA the used DAP value was defined by STUK[7]. The average effective doses for CT examinations were based on STUK measurements in a standard phantom. From the CT equipment in 2005, 80 % were measured. The method was to measure dose length product (DLP_w) of the whole procedure in a single measurement[10]. The average DLP_w values were defined and the average effective doses calculated for each procedure taking into account the type of the CT equipment (1, 2–4, 6–10 and 16 and more slice CT). The conversation factors were taken from the literature[11].

The collective effective doses to the population were estimated for X-ray procedures using the most accurate method by using the national coding system and Top 20 method. Categorising of procedures for the latter was done in co-operation with a consultative radiologist. The dose to the population from NM procedures was estimated using the factors given by ICRP[12–14]. In addition a

comparison of the collective effective dose in plain radiography obtained using the new (ICRP 103[15]) and old (ICRP 60[16]) tissue weighting factors was made.

The population of 5.32 million (in the end of 2008) was used for estimating collective effective dose per inhabitant.

RESULTS AND DISCUSSION

Estimation of the collective effective dose

The collective effective dose from all X-ray procedures in 2008 was 2414 man Sv and from NM procedures in 2009 was 172 man Sv, i.e. 0.45 and 0.03 mSv per inhabitant, respectively. Relative contributions from different categories of X-ray procedures are shown in Table 1.

In 2005 and 2008 the collective effective doses from all X-ray procedures were 0.43 and 0.45 mSv, respectively per inhabitant (in 1997, 0.5 mSv). From NM procedures the collective effective dose has been 0.03 mSv per inhabitant since year 2000.

About 50 % of the collective effective dose from X-ray examinations was caused by CT in 2005 (in 1997 only 20 %), and in 2008 it increased to 58 %. The proportion of CT procedures was only 8 % in 2008.

Plain radiography, contrast enhanced radiography and interventional radiology contributed each 13–16 % to the collective effective dose. Since 2005 the collective effective dose from plain radiography has decreased from 0.08 to 0.07 mSv per inhabitant. In two other categories the doses are unchanged.

In plain radiography the proportion of lumbar spine examinations is only 4 %, but the contribution to the collective effective dose is 29 %. Both chest radiography and examinations of pelvis and hip contribute each 20 % to the dose.

Normal dental radiology is excluded in the estimation of collective effective dose in Finland from historical reasons. In 2008 the dose per inhabitant was 0.003 mSv.

The collective effective dose estimated by the Top 20 method is reported to represent 70–90 % of the real collective effective dose[2]. The Finnish result of 77 % is consistent with that (Table 2).

In Finland only barium follow of the suggested Top 20 procedures is among the most frequent contrast enhanced radiography procedures. Barium meal was a rare procedure in 2008 in Finland. Instead, more frequent procedures were contrast enhanced fluoroscopy of biliary and pancreatic ducts. However, its contribution to the total Top 20 collective effective dose is only 1 %.

The only interventional procedure among Top 20 procedures is PTCA. In Finland other procedures like blockade of a nerve root have a remarkable contribution to the dose.

Using the Top 20 method, the impact of the new tissue weighting factors from ICRP 103 on collective effective dose from plain radiography is shown in Table 3. The impact is highest on the chest, breast and neck regions (increase 29–135 %).

The new tissue weighting factor by the ICRP for breast tissue has increased 58 %. That is the main reason for the 22 % increase of the collective effective dose in plain radiography. The decrease of the weighting factors for tissues in the regions of pelvis and abdomen has decreased the proportional contribution from examinations of those anatomical areas of 10–18 %. The biggest change (135 %) is the increased influence of mammography examinations to the collective effective dose from plain radiography with a relative proportion of 31 %.

Since year 1997 the collective effective dose from X-ray procedures has been unchanged, although the contribution of different categories of procedures has varied. Compared to the trend of increased doses reported by UNSCEAR[17] this is exceptional. Among 12 European countries, the collective

Table 1. The collective effective doses to the population in Finland from diagnostic x-ray procedures in year 2008.

Category of X-ray procedures	Collective effective dose per inhabitant (mSv)	Relative proportion of the total collective effective dose (%)
Plain radiography	0.07	16
Contrast enhanced radiography	0.06	12
CT	0.26	58
Interventional radiology	0.06	14
Total	0.45	100

Table 2. Comparison between the most accurate method and the Top 20 method to estimate the collective effective dose.

Category of X-ray procedures	Collective effective dose (man Sv)	Collective effective dose by Top 20 (man Sv)	Difference (%)
Plain radiography	388.959	394.088	1
Contrast enhanced radiography	290.054	158.377	−45
CT	1399.683	1170.956	−16
Interventional radiology	335.740	140.086	−58
Total	2414.436	1863.507	−23

Table 3. Collective effective doses from plain radiography using Top 20 method with tissue weighting factors from ICRP 60 and ICRP 103.

Top 20 no.	Procedure	Collective effective dose by ICRP 60 (man Sv)	Collective effective dose by ICRP 103 (man Sv)	Difference (%)
1	Chest	78.266	100.628	29
2	Cervical spine	8.237	16.473	100
3	Thoracic spine	12.998	13.664	5
4	Lumbar spine	114.413	101.701	−11
5	Mammography	62.931	147.887	135
6	Abdomen	40.558	36.502	−10
7	Pelvis and hip	76.686	63.153	−18
Total		394.089	480.008	22

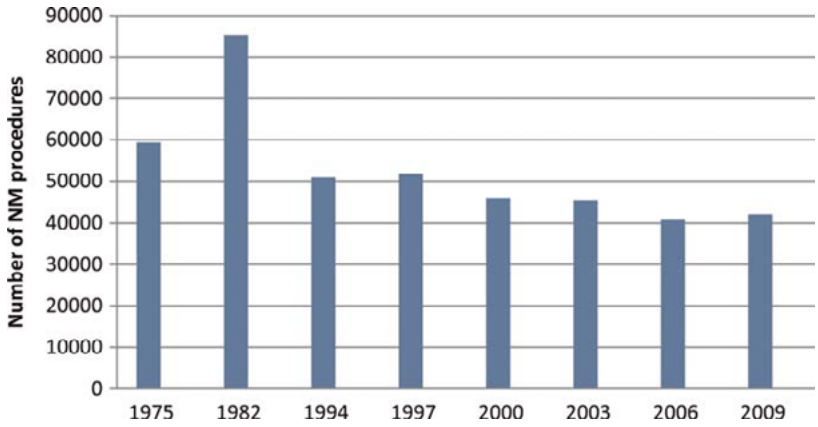

Figure 1. Number of NM examinations in Finland in 1975–2009.

effective dose from X-ray examinations in Finland is second lowest[18]. One reason for these results may be due to the awareness of patient doses and optimisation. STUK has actively disseminated information on optimisation of X-ray procedures on regular on-site inspections and workshops. A special emphasis has been given to CT.

In NM the number of PET examinations is increasing and especially the use of ^{18}F radiopharmaceuticals. Moreover, PET-CT procedures are increasing and the number of them in 2009 was 3324, which was about 8 % of all diagnostic NM procedures. The low-dose CT attenuation correction is used mainly in cardiovascular procedures and the number of these procedures was 1298 in 2009.

The slight decrease in the number of NM examinations is shown in Figure 1. However, the collective effective dose has been the same per inhabitant since 2000. The biggest change is the increased number of PET procedures from 2494 in 2006 to 4258 in 2009. The collective effective dose from PET examinations is mainly due to the use of the ^{18}F radiopharmaceuticals. The use of ^{15}O has negligible influence on the collective effective dose. The contribution of the use of the ^{11}C radiopharmaceuticals to the collective effective dose from NM procedures is only 0.3 %.

Reliability of the results

STUK has a register of all users of radiation in Finland. In the regulation, STUK is authorised to estimate collective doses from radiological procedures in the country. Almost 100 % collection result of frequencies of procedures reduces uncertainties of estimated collective effective doses. In the cohorts of patient dose, collections of the dose displays have been verified and all results have been checked by experts in STUK.

CONCLUSIONS

In Finland the collective effective dose from X-ray and NM procedures has remained stable over >10 y.

comparison of the collective effective dose in plain radiography obtained using the new (ICRP 103[15]) and old (ICRP 60[16]) tissue weighting factors was made.

The population of 5.32 million (in the end of 2008) was used for estimating collective effective dose per inhabitant.

RESULTS AND DISCUSSION

Estimation of the collective effective dose

The collective effective dose from all X-ray procedures in 2008 was 2414 man Sv and from NM procedures in 2009 was 172 man Sv, i.e. 0.45 and 0.03 mSv per inhabitant, respectively. Relative contributions from different categories of X-ray procedures are shown in Table 1.

In 2005 and 2008 the collective effective doses from all X-ray procedures were 0.43 and 0.45 mSv, respectively per inhabitant (in 1997, 0.5 mSv). From NM procedures the collective effective dose has been 0.03 mSv per inhabitant since year 2000.

About 50 % of the collective effective dose from X-ray examinations was caused by CT in 2005 (in 1997 only 20 %), and in 2008 it increased to 58 %. The proportion of CT procedures was only 8 % in 2008.

Plain radiography, contrast enhanced radiography and interventional radiology contributed each 13–16 % to the collective effective dose. Since 2005 the collective effective dose from plain radiography has decreased from 0.08 to 0.07 mSv per inhabitant. In two other categories the doses are unchanged.

In plain radiography the proportion of lumbar spine examinations is only 4 %, but the contribution to the collective effective dose is 29 %. Both chest radiography and examinations of pelvis and hip contribute each 20 % to the dose.

Normal dental radiology is excluded in the estimation of collective effective dose in Finland from historical reasons. In 2008 the dose per inhabitant was 0.003 mSv.

The collective effective dose estimated by the Top 20 method is reported to represent 70–90 % of the real collective effective dose[2]. The Finnish result of 77 % is consistent with that (Table 2).

In Finland only barium follow of the suggested Top 20 procedures is among the most frequent contrast enhanced radiography procedures. Barium meal was a rare procedure in 2008 in Finland. Instead, more frequent procedures were contrast enhanced fluoroscopy of biliary and pancreatic ducts. However, its contribution to the total Top 20 collective effective dose is only 1 %.

The only interventional procedure among Top 20 procedures is PTCA. In Finland other procedures like blockade of a nerve root have a remarkable contribution to the dose.

Using the Top 20 method, the impact of the new tissue weighting factors from ICRP 103 on collective effective dose from plain radiography is shown in Table 3. The impact is highest on the chest, breast and neck regions (increase 29–135 %).

The new tissue weighting factor by the ICRP for breast tissue has increased 58 %. That is the main reason for the 22 % increase of the collective effective dose in plain radiography. The decrease of the weighting factors for tissues in the regions of pelvis and abdomen has decreased the proportional contribution from examinations of those anatomical areas of 10–18 %. The biggest change (135 %) is the increased influence of mammography examinations to the collective effective dose from plain radiography with a relative proportion of 31 %.

Since year 1997 the collective effective dose from X-ray procedures has been unchanged, although the contribution of different categories of procedures has varied. Compared to the trend of increased doses reported by UNSCEAR[17] this is exceptional. Among 12 European countries, the collective

Table 1. The collective effective doses to the population in Finland from diagnostic x-ray procedures in year 2008.

Category of X-ray procedures	Collective effective dose per inhabitant (mSv)	Relative proportion of the total collective effective dose (%)
Plain radiography	0.07	16
Contrast enhanced radiography	0.06	12
CT	0.26	58
Interventional radiology	0.06	14
Total	0.45	100

Table 2. Comparison between the most accurate method and the Top 20 method to estimate the collective effective dose.

Category of X-ray procedures	Collective effective dose (man Sv)	Collective effective dose by Top 20 (man Sv)	Difference (%)
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Total	2414.436	1863.507	−23

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Collective effective dose in Europe from X-ray and nuclear medicine procedures. Radiation Protection Dosimetry 165 (1—4): 129—132.

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COLLECTIVE EFFECTIVE DOSE IN EUROPE FROM X-RAY AND NUCLEAR MEDICINE PROCEDURES

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Population doses from radiodiagnostic (X-ray and nuclear medicine) procedures in Europe were estimated based on data collected from 36 European countries. For X-ray procedures in EU and EFTA countries (except Liechtenstein) the collective effective dose is 547 500 man Sv, resulting in a mean effective dose of 1.06 mSv per caput. For all European countries included in the survey the collective effective dose is 605 000 man Sv, resulting in a mean effective dose of 1.05 mSv per caput. For nuclear medicine procedures in EU countries and EFTA (except Liechtenstein) countries the collective effective dose is 30 700 man Sv, resulting in a mean effective dose of 0.06 mSv per caput. For all European countries included in the survey the collective effective dose is 31 100 man Sv, resulting in a mean effective dose of 0.05 mSv per caput.

INTRODUCTION

Recent increases in medical imaging, particularly with respect to computed tomography (CT) and other high dose procedures, have led to a significant increase of individual patient doses and of the collective dose to the population as a whole. Regular assessments of the magnitude and distribution of this large and increasing source of population exposure are therefore of high importance. The objective of the present Dose Datamed 2 (DDM2) project has been to collect available data on the doses from radiodiagnostic procedures (X-ray procedures and nuclear medicine, later NM) in Europe and to facilitate the further implementation of Radiation Protection 154, European Guidance on Estimating Population Doses from Medical X-Ray Procedure[(1)]. In that guidance the Top 20 method was introduced to include the 20 types of examinations or procedures that are amongst the highest contributors to the collective effective dose. Together these 'Top 20 Exams' contribute between 50 and 70 % to the total frequency and between 70 and 90 % of the total collective effective dose from all medical X-ray procedures (excluding dental).

An estimate of the collective effective doses to patients from radiodiagnostic procedures for Europe as a whole has not been previously carried out. In the previous Dose Datamed1 (DDM1) project, collective effective doses were also surveyed but only for 10 European countries; therefore, the present survey for all European countries was much more comprehensive.

MATERIALS AND METHODS

Data were collected using electronic questionnaires and Excel sheets that were sent to national contact persons identified for the project. The actual dose survey for population dose estimations (i.e. the frequency and dose data) was implemented through specific Excel files. Templates of those Excel spreadsheets have been integrated into the on-line system for download and the completed files have been collected there within an integrated upload feature.

In this study, for the determination of the collective effective dose, the general population has been used instead of the patient population, and no distinction has been made between adult and paediatric populations. This pragmatic approach is justified for several reasons related to the availability and comparability of the data and the deficiency of effective dose as a risk quantity for patient population.

The overall collective effective dose is the real reported dose for only six countries (BG, CH, DE, FI, FR and UK). For the other countries, which could report only Top 20 data, the overall collective effective dose have been obtained from the Top 20 total collective effective dose by using a correction factor that takes into account the procedures not included in the Top 20. This correction factor has been defined as the average ratio between the overall total collective effective dose and the Top 20 total collective effective dose (total overall/total Top 20), for each main group of X-ray procedures (plain radiography, fluoroscopy, CT and interventional radiology), calculated from the results for the six countries of this survey which have reported both types of total collective effective doses (BG, CH, DE, FI, FR and UK).

RESULTS

For X-ray procedures in EU countries and EFTA countries (except Liechtenstein) (later Group 1) the

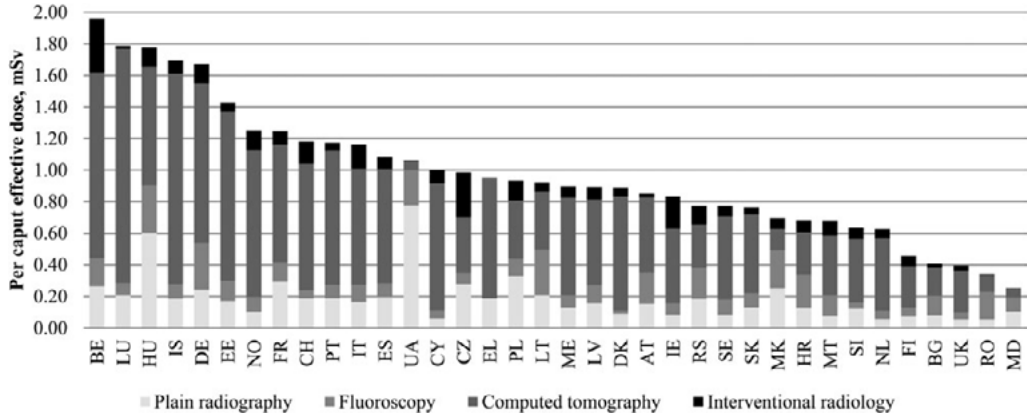

Figure 1. Per caput effective doses for different countries from X-ray procedures. For EL, data for the contributions of fluoroscopy and IR were not available.

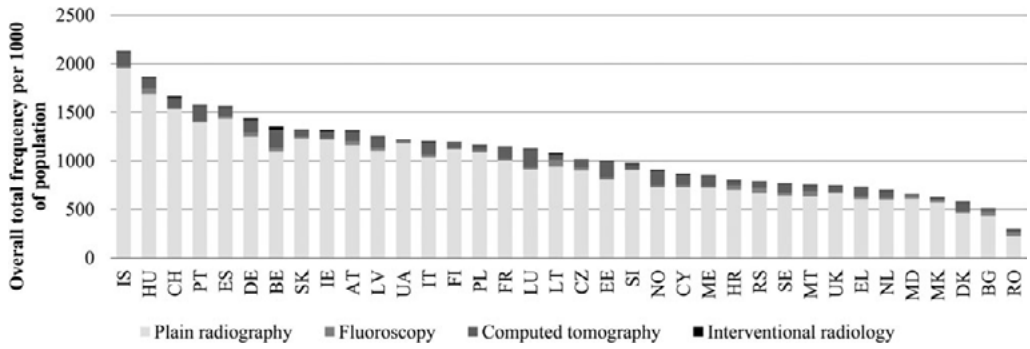

Figure 2. Frequencies per 1000 of population for different countries. The relative contributions of the four main groups (plain radiography including dental, fluoroscopy, CT and interventional radiology) are also shown.

collective effective dose is 547 500 man Sv, resulting in a mean effective dose of 1.06 mSv per caput. For all European countries included in the survey (later Group 2) the collective effective dose was 605 000 man Sv, resulting in a mean effective dose of 1.05 mSv per caput. The per caput effective doses for plain radiography, CT, fluoroscopy and interventional radiology in each country are presented in Figure 1 and frequencies of procedures, respectively, in Figure 2.

The collective effective dose for NM procedures is in

- Group 1: 30 700 man Sv, resulting in a mean effective dose of 0.06 mSv per caput.
- Group 2: 31 100 man Sv, resulting in a mean effective dose of 0.05 mSv per caput.

The total collective effective dose for diagnostic X-ray and NM procedures in European countries is in

- Group 1: 578 200 man Sv, resulting in a mean effective dose of 1.12 mSv per caput.
- Group 2: 636 000 man Sv, resulting in a mean effective dose of 1.10 mSv per caput.

The contribution of the NM examinations to the total per caput effective dose from all medical imaging is relatively small, on the average 5 %, while there are high variations in the contribution between the countries, from 0.4 to 14.5 % (Table 1).

The contribution to the total population dose of CT, plain radiography, fluoroscopy, interventional radiology and NM procedures is shown in Figure 3.

DISCUSSION

The overall per caput effective doses are about half the recent value of per caput effective doses estimated in Australia[2] and about one-third of the

Table 1. Comparison of European mean per caput effective dose for X-ray and NM procedures.

Country	Overall per caput *E*, X rays, mSv	Overall per caput *E*, NM, mSv	Overall per caput *E*, X rays + NM, mSv	Contribution of NM to the overall X rays + NM, %
AT	0.85	0.07	0.92	76
BE	196	na	na	Na
BG	0.41	0.01	042	2.2
CH	1.18	0.05	1.23	3.8
CY	1.00	0.02	1.02	2.1
CZ	0.99	0.03	1.02	3.3
DE	1.67	0.08	1.75	4.6
DK	0.89	0.07	0.96	7.6
EE	1.43	0.01	1.44	0.7
EL	0.95	0.16	1.11	14.5
ES	1.08	0.07	1.15	5.7
FI	0.45	0.02	0.48	5.2
FR	1.25	0.09	1.34	6.9
HR	0.68	0.03	0.71	4.8
HU	1.78	0.06	1.83	3.2
IE	0.83	0.02	0.86	2.8
IS	1.70	0.03	1.73	1.9
IT	1.16	0.08	1.24	6.2
LT	0.92	0.01	0.93	1.1
LU	1.79	0.15	1.94	7.7
LV	0.89	0.01	0.90	1.1
MD	0.25	0.02	0.27	7.4
ME	0.90	0.01	0.91	1.3
MK	0.70	0.01	0.71	1.4
MT	0.68	0.03	0.71	4.0
NL	0.63	0.05	0.67	7.0
NO	1.25	0.03	1.28	2.1
PL	0.93	0.05	0.98	5.4
PT	1.17	0.08	1.25	6.2
RO	0.34	0.00	0.34	0.5
RS	0.77	0.02	0.79	2.0
SE	0.77	0.03	0.80	3.6
SI	0.63	0.06	0.69	8.2
SK	0.76	0.02	0.79	2.8
UA	1.06	0.00	1.06	0.4
UK	0.39	0.02	0.42	5.9

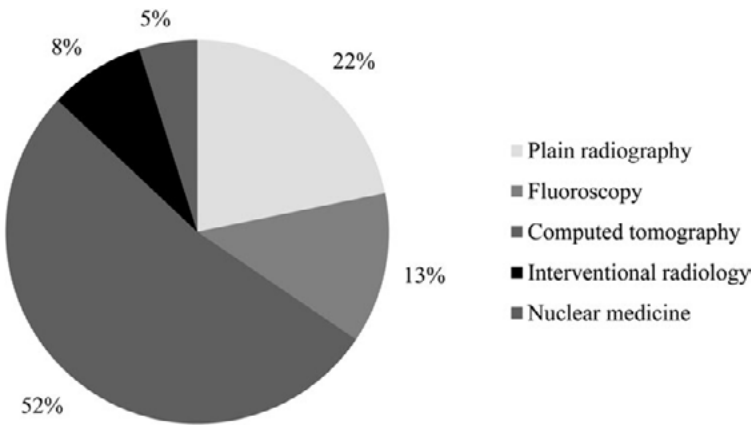

Figure 3. Contribution of the main groups of X-ray procedures and NM procedures to the total collective effective dose for Group 2 countries (all 36 countries).

corresponding value in the USA[3]. Comparing the results with an earlier estimation of population dose in Europe, in the DDM1 countries, there seems to be a trend upwards; however, because for part of the DDM1 countries the new data are based on Top 20 estimations only, no strict conclusion about the percentage increase can be made. While the average dose in Europe turned out to be relatively low, there are high variations of the results between countries.

The importance of age/sex distributions was also reviewed. Based on EUROSTAT data, the overall age distribution of the EU 27 countries shows no significant differences between the data from 2005 and 2010. Comparisons of the average data on age/sex distribution for the five DDM 1 countries and four DDM 2 countries, for specific X-ray examinations, indicated that the distributions are sufficiently similar to conclude that the usage of the European average distributions (published in DDM1 project) is still reasonable when specific national data on age and sex distribution per examination are not available. Although a relatively low value of population dose can be a good sign for the successful implementation of the justification and optimisation principles in radiation protection, it could also be attributed to the lack of imaging resources. On the other hand, a relatively high value should imply considerations on whether the justification and optimisation principles are properly implemented.

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REFERENCES

1. European Guidance on Estimating Population Doses from Medical X-ray Procedures and Annexes. Radiation Protection No. 154. European Commission, Directorate General for Energy and Transport (2008).
2. Hayton, A., Wallace, A., Marks, P., Edmonds, K., Tingey, D. and Johnston, P. *Australian per caput dose from diagnostic imaging and nuclear medicine*. Radiat. Prot. Dosim. **156**(4), 445–450 (2013).
3. NCRP. *Ionizing radiation exposure of the population of the United States*. NCRP Report 160. National Council on Radiation Protection and Measurements (NCRP) (2009).

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TOROI P, KAIJALUOTO S, BLY R (2015):
Patient exposure levels in radiotherapy CT simulations in Finland.
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PATIENT EXPOSURE LEVELS IN RADIOTHERAPY CT SIMULATIONS IN FINLAND

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Computed tomography (CT)-based simulation is an essential part of the radiotherapy treatment process. Patient exposure levels in CT simulations were collected from 15 CT systems from all 13 Finnish radiation therapy centres. A large standard deviation up to 56 % in dose levels between CT systems was noticed. Average volumetric CT dose indexes (in body phantom) were 24, 18 and 29 mGy for prostate, resection breast and head and neck treatment targets, respectively, and 70 mGy (in head phantom) for whole brain. These average dose indexes were much higher than those in corresponding diagnostic imaging in Finland. Dose levels in simulations with some devices were even over 3-fold higher than the diagnostic reference level for the same area of interest. Moreover, large variations in other exposure parameters, such as pitch and slice thickness, were seen. The results were discussed nationally, and general guidance to optimise dose levels was shared.

INTRODUCTION

A cancer patient may go through many computed tomography (CT) examinations in a process spanning from diagnosis to treatment and patient exposure to radiation accumulates. The CT dose quantities displayed by the CT system are the volumetric CT dose index ($CTDI_{vol}$) and the dose–length product (DLP). These quantities are not direct patient doses, but they are related to patient exposure and therefore useful parameters for a technical comparison of different CT systems. Patient exposure levels in diagnostic computed tomography have been estimated in many papers, and diagnostic dose reference levels (DRLs) are given[1, 2]. At the moment, Finnish DRLs using $CTDI_{vol}$ for abdomen and body examinations are 12 mGy, and for head examinations 55 mGy. However, patient exposures from CT simulations for radiotherapy have not been a concern so far, and there is not much information available on the dose levels from CT simulations.

In treatment planning, a set of CT images is used for electron density calculation, generating digitally reconstructed radiographs (DRRs), and in some cases also for contouring the target and other relevant organs. The different aims of the simulation and diagnostic imaging also set different requirements in terms of image quality. Therefore, appropriate exposure parameters and the dose level should be assessed for this purpose. CT should provide accurate information about patient geometry and tissue composition. The most important image quality objective would probably be avoiding image artefacts. For diagnostic imaging, the requirements for resolution and contrast are typically higher than those for simulation, as in the simulation, there is only a limited need for separating soft tissues from each other, and the detection of small objects is rarely of interest. In cases where a soft tissue is an issue, such as in delineating prostate from surrounding tissues, MRI images are used in parallel to CT images and in some cases high density markers are implanted during the surgery. Moreover, treatment planning is increasingly completed with PET imaging.

Specific requirements for CT simulators are mostly related to HU conversion, laser accuracy and table movements[3–8]. Guidance given for diagnostic CTs[7, 8] is generally referred to when image quality and dosimetric issues are discussed. For the selection of exposure parameters, specific oncology protocols are recommended and often provided by manufacturer[3, 4, 6, 7].

A predetermined tube voltage should be used so that HU values can be converted to electron density correctly. A tube voltage of 120 kV is generally used, but 130 kV might also be useful if dose calculation is adjusted accordingly. Slice thickness can be selected locally based on the target, CT capabilities, and opinions of oncologists. Large variation of 1.25–5 mm in the selected slice thickness can be seen in the literature [e.g. (3, 7)]. Liu *et al.*[6] have compiled a summary on optimal acquisition parameters. They recommend that pitch values of >1 should not be used in CT simulation due to possible artefacts. However, in the IAEA guidelines[7], pitch values from 1.5 to 2 are recommended, most likely for reasons of better efficiency.

Requirements relating to patient exposure generally concern the accuracy of the dose display and not actual patient exposure[4, 5, 7]. Radiation dose levels from imaging for a cancer patient have not been a major concern because of the high dose they will

receive during the treatment. Concomitant dose levels outside of the treatment volume are very much dependent on particular treatment scenario. As an order of magnitude at a distance of 10 cm from a 10 × 10 cm treatment field, the target gets ~1 % of the treatment dose[9]. So, with 50 Gy, it would get ~500 mGy. This level corresponds to several cumulative CT examinations. However, if patients survive the primary cancer, they may have a long life expectancy and the associated risk from additional imaging should be kept as low as reasonably achievable.

In this study, the dose levels displayed for some of the most conventional CT simulations were collected and compared with Finnish diagnostic dose reference levels. Other exposure parameters were also collected and summarised.

MATERIALS AND METHODS

A questionnaire was sent to all 13 Finnish radiation therapy centres. Data for a minimum of 10 average-sized patients (weights of 60–90 kg) were requested, including displayed $CTDI_{vol}$ and DLP values in CT simulations and information on the phantom used for dose display calibration. Other exposure parameters such as pitch, collimation, dose modulation, etc. were also requested. The survey covered the following treatment targets: prostate, resection breast, head and neck and whole brain.

Doses for whole brain scans have been documented based on the CTDI head phantom. If the result was given for the body phantom, it was multiplied by a factor of 2. Doses for scans of all other targets were documented based on the CTDI body phantom. If the result was given for the head phantom, it was divided by the factor of 2. The use of this technical conversion factor of 2 can be justified e.g. based on the results of AAPM[10].

Table 1. CT devices in the survey.

Manufacturer	Model	Maximum number of slices
GE	GE HiSpeed QX/i/	4
	Lightspeed	4
	Lightspeed RT	4
	LightSpeed RT4	4
	GE LightSpeed RT-16 Xtra	16
Philips	Brilliance CT Big Bore	16
Siemens	Emotion 6	6
	Somatom Sensation Open	16
	Somatom Definition AS	20
	Sensation Open	24
	Biograph mCT S(40)	40
	Sensation Open	40
Toshiba	Aquilion	16
	Aquilion LB	16
	Toshiba Aquilion LB	16

RESULTS

CT devices

Data were received from all 13 hospitals and for 15 CT systems (Table 1). For the dose results, the systems are numbered in occasional order for confidentiality. However, it can be concluded that there was no clear correspondence between dose level and CT device type or manufacturer. Both lower and higher dose levels were observed for each CT manufacturer with several CT device represented in this questionnaire.

Exposure parameters

A summary of collected exposure parameters is given in Table 2. Both iterative and filtered back-projection reconstruction were in use. There was no clear correspondence between dose levels and the selected exposure parameters, such as tube voltage, field of view, pitch or slice thickness. For example, users did not select a lower dose level even if a larger slice thickness or pitch was in use. It seems that the dose level is selected separately. The range of manufacturer-specific reference milliampere second and noise index values

Table 2. Summary of collected exposure parameters.

	Prostate	Resection breast	Head and neck	Whole brain
Tube voltage (kV)	120–140	120–140	120–135	120
Slice thickness (mm)	0.5–2.5	0.5–2.5	0.5–2.5	0.5–2.5
Rotation time (s)	0.5–1	0.44–1	0.5–1	0.5–1
Pitch	0.7–1.5	0.562–1.5	0.55–1.2	0.55–1.375
Scan length: average (cm)	34	36	36	25
Min–max (cm)	21–47	22–51	16–63	17–34
Reference milliampere second (Siemens)	105–210	75–150	75–250	350–370
Noise index (GE)	16–22.4	12–21.2	3.8–9	2.6–3.8
Slice thickness (mm)	0.5–2.5	0.5–2.5	0.5–2.5	0.5–2.5

are shown based on the data reported by hospitals for Siemens and GE systems.

Dose levels

$CTDI_{vol}$ values for radiotherapy simulations of prostate, resection breast, head and neck, and whole brain are given in Figures 1–4, respectively. Each bar represents one patient so that inter-patient variation can be seen. Average values were calculated for each target and CT device. To be able to estimate national dose level and inter-scanner variation, the average, third quartile, minimum, maximum and standard deviation of these results are given in Table 3.

DISCUSSION

There was a large amount of variation in the exposure parameters used for CT simulations. Exposure parameters are often selected based on the default settings recommended by the manufacturer. Additional and continuous optimisation is typically not performed for these CT systems. It should be kept in mind that some of these parameters not only affected patient exposure but also image quality, which should not be spoiled by non-optimal exposure parameters.

Surprisingly, tube voltages other than 120 kV were used in some places. Slice thickness was 2.5 mm or below in all cases, and this complies with recommendation of 3 mm[7]. Pitch values of >1 were generally

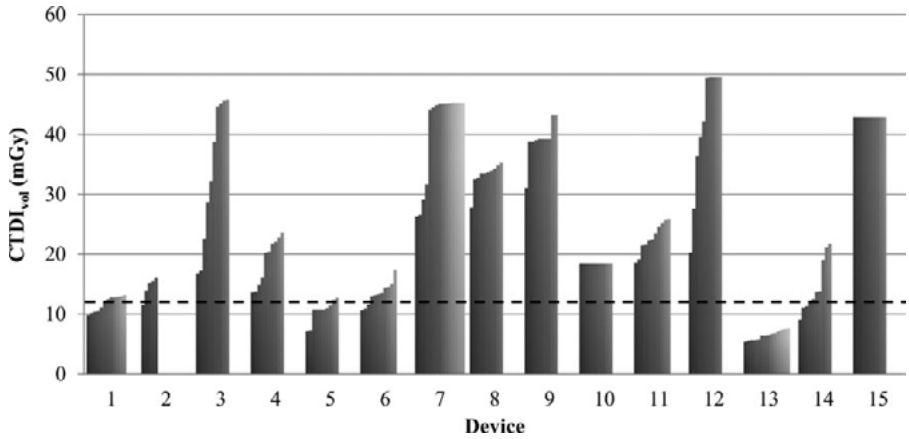

Figure 1. Body phantom CTDIvol values in CT simulation for prostate. A diagnostic reference level of 12 mGy for body examinations is marked here for comparison purposes.

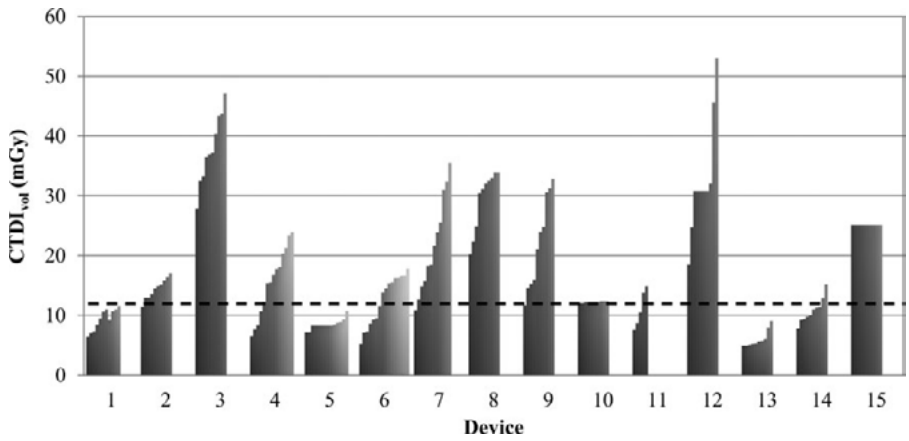

Figure 2. Body phantom CTDIvol values in CT simulation for resection breast. A diagnostic reference level of 12 mGy for body examinations is marked here for comparison purposes.

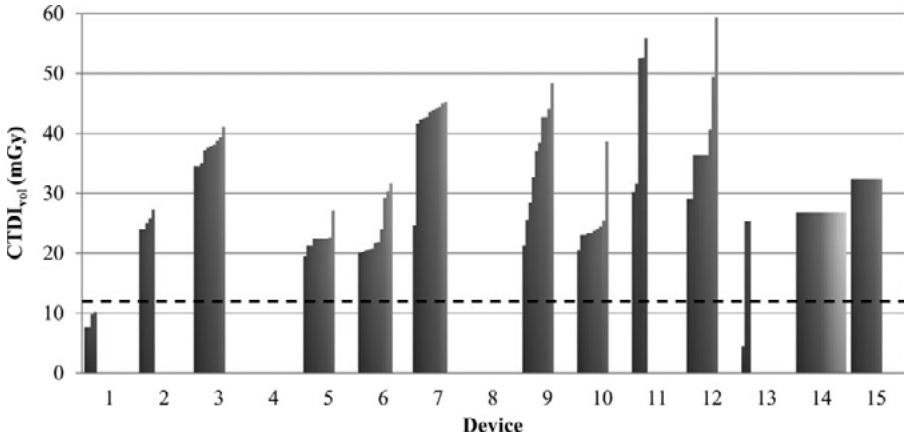

Figure 3. Body phantom CTDIvol values in CT simulation for head and neck. A diagnostic reference level of 12 mGy for body examinations is marked here for comparison purposes.

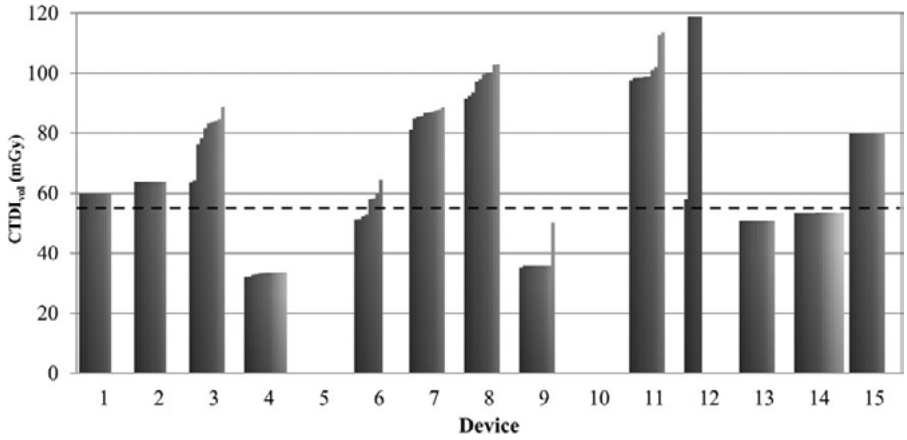

Figure 4. Head phantom CTDIvol values in CT simulation for whole brain. A diagnostic reference level of 55 mGy for head examinations is marked here for comparison purposes.

used, contrary to the recommendation of Liu *et al.*[6] However, the pitch values used do not comply with the values of 1.5–2 recommended by IAEA[7] either. It also seems that the dose level is not adjusted in relation to the pitch or slice thickness, and this might even increase the possible differences in image quality.

As expected, the largest variation in scan length can be seen in head and neck simulation, where there was the largest variation in target volumes. For other targets, anatomical range of the target is more fixed and less variation is expected. However, the anatomical scan range is typically selected locally for different targets, and the largest variation is between hospitals.

A large amount of variation in pre-set image quality levels such as reference milliampere second and noise index can be seen. The effect of this can also be seen in standard deviations of 35–56 % for dose levels between different devices. Minor or lack of dose modulation and inter-patient variation is also noteworthy with some devices. Dose levels are also generally higher than those used in diagnostics. Only 23 % of the calculated average doses would comply with the established national DRLs, whereas 34 % of values were over 2-fold higher than the DRL. The results are comparable with the results of Garcia-Ramirez *et al.*[11] who reported dose levels of 1–2 cGy

Table 3. Summarised dose results.

Target	Number of CT systems involved	Average $CTDI_{vol}$ (mGy) values (min–max)	Third quartile (mGy)	SD of $CTDI_{vol}$ (%)
Prostate	15	24 (6–43)	36	53
Resection breast	15	18 (6–38)	24	54
Head and neck	13	29 (9–45)	37	35
Whole brain	13	70 (33–107)	86	35

higher when large bore CT was compared with normal diagnostic CT.

The justification for the higher dose levels than needed for diagnostic imaging was questioned by the radiation protection authority in the annual meeting with radiation therapy physicists. Some of the CT simulators with the lowest dose levels in simulations are also used for diagnostic imaging and, therefore, their dose levels are probably more optimised. Moreover, the survey results show that, for each simulated target area, there was at least one hospital using dose levels that do not exceed the corresponding DRLs. However, these hospitals were still satisfied with the image quality. A national recommendation was given to optimise dose levels, and the Radiation and Nuclear Safety Authority (STUK) will follow up on the dose levels within a year.

In the survey, there were a limited number of pieces of equipment from each manufacturer, and therefore, a comparison between different manufacturers' CT dose levels cannot be carried out because it would also reveal the dose levels of individual hospitals. However, it can be concluded that there was no direct correspondence between dose level and CT device type.

Dose levels were collected as they were displayed by the system, and this adds some additional uncertainty to the results. National acceptability criterion for the uncertainty of dose display is <25 %. However, some of the oldest Toshiba systems might still give $CTDI_{vol}$ values, which are based on the maximum tube current instead of the average value. This might distort some of the results from Toshiba systems.

CT simulation is only one part of the diagnostic and therapy process; therefore, other related exposures should also be evaluated. There is lot of work ongoing to evaluate dose levels in image-guided radiotherapy [e.g. (12)]. This kind of imaging is repeated several times during the treatment process, thus highlighting its importance.

CONCLUSIONS

There is a large amount of variation in the dose levels and exposure parameters used for CT simulations. Patient exposure levels are generally much higher than those used for diagnostics. Exposure parameters should be reviewed and optimised together with the dose level.

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REFERENCES

1. European Commission (EC). *European Guidance on Quality Criteria for Computed Tomography*. EUR 16262 EC (1999).
2. Pantos, I., Thalassinou, S., Sargentos, S., Kelekis, N. L., Panayiotakis, G. and Efestathopoulos, E. P. *Adult patient radiation doses from non-cardiac CT examinations: a review of published results*. Br. J. Radiol. **84**, 293–303 (2011).
3. Aird, E. G. A. and Conway, J. *CT simulation for radiotherapy treatment planning*. Br. J. Radiol. **75**, 937–949 (2002).
4. Mutic, S., Palta, J., Butker, E. K., Das, I. J., Huq, M. S., Loo, L. -N. D., Salter, B. J., McCollough, C. H. and Van Dyk, J. *Quality assurance for computed-tomography simulators and the computed-tomography-simulation process: report of the AAPM Radiation Therapy Committee Task Group No. 66*. Med. Phys. **30**(10), 2762–2792 (2003).
5. Canadian Association of Provincial Cancer Agencies (CAPCA). *Standards for quality control at Canadian Radiation Treatment Centers, CT-Simulators*. CAPCA (2007).
6. Liu, R. R., Prado, K. L. and Cody, D. *Optimal acquisition parameter selection for CT simulators in radiation oncology*. J. Appl. Clin. Med. phys. **9**(4), 2762–2792 (2008).
7. International Atomic Energy Agency (IAEA). *Quality Assurance Programme for Computed Tomography: Diagnostic and Therapy Applications*. IAEA Human Health Series No. 19. IAEA (2012).
8. European Commission (EC). *Criteria for acceptability of medical radiological equipment used in diagnostic radiology, nuclear medicine and radiotherapy*. Radiation protection N° 162. Publication Office of the European Union (2012).
9. Stovall, M., Blackwell, C. R., Cundiff, J., Novack, D. H., Palta, J. R., Wagner, L. K., Webster, E. W. and Shalek, R. J. *'Fetal dose from radiotherapy with photon beams: report of AAPM Radiation Therapy Committee Task Group*. Med. Phys. **36**(22), 63–82 (1995).

10. AAPM Report No. 204. *Size-specific dose estimates (SSDE) in pediatric and adult body CT examinations.* American Association of Physicists in Medicine (2011).
11. Garcia-Ramirez, J. L., Mutic, S., Dempsey, J. F., Low, D. A. and Purdy, J. A. *Performance evaluation of an 85-cm-bore x-ray computed tomography scanner designed for radiation oncology and comparison with current diagnostic CT scanners.* Int. J. Radiat. Oncol. Biol. Phys. **54**(4), 1123–1131 (2002).
12. Murphy, M. J. *et al. The management of imaging dose during image-guided radiotherapy: report of the AAPM Task Group 75.* Med. Phys. **34**(10), 4041–4063 (2007).

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CONTEMPORARY COLLECTIVE EFFECTIVE DOSE TO THE POPULATION FROM X-RAY AND NUCLEAR MEDICINE EXAMINATIONS—CHANGES OVER LAST 10 YEARS IN FINLAND

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Contemporary collective effective doses to the population from x-ray and nuclear medicine examinations in Finland in 2018 was estimated. The estimated effective dose per caput from x-ray examinations increased from year 2008 to 2018 respectively from 0.45 mSv to 0.72 mSv and from nuclear medicine examinations from 0.03 mSv to 0.04 mSv. The proportional dose due to CT examinations of the total collective effective dose from all x-ray examinations increased from 58% in 2008 to 70% in 2018 and the dose did not change substantially in total when new conversion factors were applied. The collective effective dose from conventional plain radiography did not change substantially during the last ten years while the new (ICRP 103) tissue weighting factors were taken into use in 2018, however frequencies of examinations in total decreased. The collective effective dose from CT in nuclear medicine tripled between 2009 and 2018.

The European Council Directive 2013/59/EURATOM (Basic Safety Standard)[1] defines the legal requirements for radiation protection of individuals submitted to medical exposures in the European Union. According to Article 64, the Member States shall ensure that the distribution of individual dose estimates from medical exposure for radiodiagnostic and interventional radiology purposes is determined for the population.

In 2008 EC published practical guidance on estimating population doses from medical X-ray procedures (RP 154)[2]. In 2014 EC published results from a European survey on population doses in Europe[3].

In Finland the collective effective doses to the population from X-ray and nuclear medicine (NM) examinations have been estimated regularly in few years' periods over 20 years. During the first 10 years, the changes had been minimal, but the propositional dose due to CT examinations had already increased from 2005 to 2008 from 50 to 58%[4].

METHODS

Collection of frequencies of procedures

The frequencies of examinations in 2018 were collected by questionnaires sent to all X-ray and NM units in Finland. The response rates were 98% for radiology departments and private clinics, 91% for dental practices, 60% for radiotherapy units performing dose planning CT and 100% for NM departments. Radiological procedures are classified in Finland using a national coding system[5] with more than 800 codes. For some procedures there are three different codes depending on the complexity of the procedure.

Effective doses from procedures

The average effective doses for plain radiography were calculated using PCXMC programme[6]. Data from a total of 1000 examinations was collected in 2006 from 35 randomly selected hospitals[4], and ICRP (103) tissue correction factors[7] were applied. In contrast-enhanced radiography and in interventional radiology, the average effective doses are based on typical air–kerma area product (KAP) values or in few cases effective doses from literature[8–11]. For some coronary procedures KAP values were collected in 2014–2016 from 18 296 procedures[12]. For the conversion from KAP values to the effective dose, conversion factors were taken from the literature[8, 9]. The average effective doses for CT examinations were based on air–kerma length product values collected in 2012 for 12 procedures from 41 radiology departments of a total of 57 CT units[13]. The correctness of dose displays of the CT equipment was verified by measurements during STUK's regular inspections. The average effective doses were calculated for each procedure using conversion factors taken from literature[2, 14, 15].The dose to the population from NM procedures was estimated using the reported mean administered activities and the conversion factors given by ICRP[16, 17]. In addition, a comparison of the collective effective dose from CT procedures obtained using the new (ICRP 103) and old (ICRP 60[18]) tissue weighting factors was made.

Table 1. The change of effective doses per caput from X-ray procedures and contributions to the total effective dose per caput in years 2008 and 2018.

	Effective dose per caput (mSv)			Contribution to total effective dose per caput (%)	
Group of procedures	2008	2018	Change (%)	2008	2018
Plain radiography	0.073	0.082	12	16	11
Contrast-enhanced radiography	0.055	0.038	−31	12	5
Computed tomography	0.26	0.50	91	58	70
Interventional radiology	0.063	0.098	57	14	14
Total	0.45	0.72	59	100	100

Table 2. The change of frequencies of X-ray procedures per 1000 population and contributions to total frequency in years 2008 and 2018.

	Frequencies per 1000 population			Contribution to total frequency (%)	
Group procedures	2008	2018	Change (%)	2008	2018
Plain radiography*	658	542	−18	89.3	80.7
Contrast-enhanced radiography	12.3	9.6	−22	1.7	1.4
Computed tomography	61.0	111	81	8.3	16.5
Interventional radiology	5.5	9.2	67	0.8	1.4
Total	737	671	−9	100	100

*Excluding dental procedures.

The collective effective doses to the population from X-ray and NM procedures were estimated using the most accurate method by using the national coding system.

The population of 5.52 million (at the end of 2018) was used for estimating the mean effective dose per caput.

RESULTS

Estimation of the collective effective dose

The collective effective dose from all X-ray procedures in 2018 was 3948 manSv and from NM procedures 215 manSv. That is 0.72 mSv and 0.04 mSv per caput, respectively. The change of effective doses per caput from 2008 to 2018 for groups of X-ray procedures and the relative contributions to the total effective doses per caput are shown in Table 1. The change of frequencies of X-ray procedures per 1000 of population from 2008 to 2018 and the relative contributions to the total frequency are shown in Table 2.

From 1997 to 2008, the effective dose per caput from all X-ray procedures had not varied much from 0.5 mSv, but until 2018 the dose has increased to 0.72 mSv (Table 1). From NM procedures the effective dose per caput had been 0.03 mSv from 2000 to 2009 but has increased until 2018 to 0.04 mSv.

The increase of the total per caput effective dose is mainly caused by the increase of per caput effective doses of CT (91%) and interventional radiology (57%). The increase of per caput effective dose in plain radiography is minor (12%), while there is a considerable decrease of the per caput effective dose in contrast-enhanced radiography (−31%).

The effective dose per caput from CT examinations has increased until 2018 to 0.50 mSv (Table 1). While in 1997 only 20% of the collective effective dose was from CT procedures, by 2018 its proportion has increased to 70%. The collective effective dose from CT procedures was 2744 manSv in 2018 when conversion factors from EC[2], based on ICRP 60 tissue weighting factors, were applied and 2728 manSv when new[15] conversion factors, based on ICRP 103 tissue weighting factors, were applied. The difference is only 0.6%. The differences between the two sets of conversion factors are shown in Table 3.

Table 3. Comparison between conversion factors (mSv/mGy cm) for CT

Body region	EC RP 154, ICRP 60 (2008)	Deak *et al.*, ICRP 103 (2010)	Difference (%)
Head	0.0021	0.0019	−9.5
Neck	0.0059	0.0052	−12
Chest	0.014	0.0146	4.3
Abdomen	0.015	0.0153	2.0
Pelvis	0.015	0.0129	−14
Trunk	0.015	not given	

The increase of frequencies of CT procedures from 2008 to 2018 was remarkable, 81% (Table 2). Their contribution to the total frequency doubled, while still remaining relative low (16.5%) compared with their contribution to the total collective effective dose (70%).

From 2005 to 2008, the effective dose per caput from plain radiography had decreased from 0.08 to 0.07 mSv but was again increased in 2018 to 0.08 mSv (12%). The contributions of plain radiography, including normal dental radiology, and contrast-enhanced radiology to the total collective effective dose decreased from 2008 to 2018, while the contribution of interventional radiology remained the same. Among these groups, the change was most remarkable for contrast-enhanced radiology (decrease from 12 to 5%).

The frequencies of both the plain radiography and contrast-enhanced radiography and their contributions to the total frequency decreased, while that of interventional radiology considerably increased. However, the contribution of interventional radiology to the total frequency remained very small (1.4%) like that of contrast-enhanced radiography.

Within plain radiography (excluding normal dental radiology), the proportion of the frequency of mammography examinations is only 13%, but the contribution to the collective effective dose of this group is 47%. Chest radiography and examinations of pelvis and hip contribute to the dose of this group 14 and 11%, respectively.

In NM the number of all PET-CT procedures is increasing, and the number of them increased from 3529 in 2009 to 12 346 in 2018, which is proportionally from 8 to 28% of all diagnostic NM procedures. The PET-CT procedures in 2018 were mainly for adults, since only 74 paediatric PET-CT procedures were performed. The number of adult SPECT-CT procedures increased from 2698 in 2009 to 8787 in 2019 (226%).

Despite the slight decrease of the total number of NM examinations, the collective effective dose has been almost the same per inhabitant since 2000. The five most contributing procedures to the collective effective dose are shown in the Table 4. The collective effective dose from PET examinations is mainly due to the use of the ^{18}F radiopharmaceuticals. The use of ^{15}O has negligible influence on the collective effective dose. The contribution of the use of the ^{11}C radiopharmaceuticals to the collective effective dose from NM procedures is only 0.8%. The collective effective dose from CT in hybrid imaging has tripled between 2009 and 2018 from 23.7 to 71.4 manSv.

DISCUSSION

Explaining factors for changes

The frequency of plain radiography excluding dental examinations decreased 18% in total during 2008–2018 (Table 2). The frequencies of radiography examinations of the head and neck and abdomen decreased 61 and 70% respectively, while that of the chest, pelvis and hip did not change substantially during 2008–2018. However, the frequency of mammography examinations increased 26% due to changes in the regulation in 2011 that widened the screening age from 50–59 to 50–69 years gradually by the end of year 2021. Moreover, the new tissue weighting factor by the ICRP 103 for breast tissue has increased 58% compared to ICRP 60. The main reason for the almost unchanged collective effective dose from plain radiography is therefore the use of new conversion factors from ICRP 103 that increases the collective effective dose by about 22%[19], i.e. the decrease of collective dose caused by the decreased frequencies is compensated by the increase of collective dose due to using the new tissue weighting factors in the calculation of effective dose per procedure.

Frequencies of CT examinations of the head and neck, chest, abdomen, pelvis and hip and trunk increased 49, 44, 95, 17 and 180%, respectively, and collective effective doses from CT examinations increased 1, 60, 99, 33 and 147%, respectively. The increase of the frequencies of CT procedures explains mostly the increase of the collective effective dose.

The main reason for the increase of the collective effective dose from interventional procedures arises from increased frequency of PTCA procedures. The total number of interventional procedures increased

Table 4. Five procedures that contribute most to the collective effective dose from NM

Procedure	Frequencies per 1000 population	Mean effective dose per procedure (mSv)	Proportion of total collective effective dose from NM (%)
Upper body or whole body metabolic PET-CT/^{18}F-FDG	1.3	9.1	31
Total body bone isotope imaging/^{99m}Tc phosphate or phosphonate	1.1	3.2	9
Heart perfusion SPECT-CT at rest and with exercise/^{99m}Tc tetrofosmin	0.25	9.6	6
Whole body extensive metabolic PET-CT/^{18}F-FDG	0.11	16	5
Whole body extensive bone SPECT-CT/^{99m}Tc phosphate or phosphonate	0.085	11	4

67% during 2008–2018 (Table 2), while the number of PTCA procedures increased 59%. On the other hand, an effective dose per a PTCA procedure decreased from 24 to 17 mSv. The new technology enables the use of pulsing beams that decrease the dose, and additionally other techniques for optimization have been promoted extensively by STUK.

Frequencies of contrast-enhanced procedures decreased a total of 22% during 2008–2018. The major contribution to the collective effective dose arises from cardio angiography (CA) procedures. The number of CA procedures increased 46% during 2008–2018, but an average effective dose per the CA procedure decreased from 6 to 3 mSv. Therefore, the considerably lower dose per procedure caused a decrease of the collective effective dose despite the increase of the frequency.

In the survey of 36 European countries[20], the average collective effective dose per caput was 1.1 mSv, and in the USA in 2016[21], it was 2.16 mSv. In Finland the collective effective dose has increased to 0.76 mSv but is still on the reasonable level compared to the above-mentioned examples. In the USA in 2016, the per caput effective dose from CT examinations was 1.37 mSv, and the number of CT examinations had increased in 10-year period 20%; in Finland in 2018 the per caput dose from CT examinations was only 0.50 mSv despite the considerable increase (81%) of the frequency of CT examinations.

Reliability of the results

STUK has a register of all users of radiation in Finland. In the regulation STUK is authorised to estimate collective doses from radiological procedures in the country. In the collection of frequency data, the response rate was 98% except for normal dental procedures (91%) and for radiotherapy dose planning CT procedures (60%). These good results reduce uncertainties of estimated collective effective doses. In the cohorts of patient dose collections, the dose displays have been verified, and all results have been checked by experts of STUK.

CONCLUSIONS

In Finland the total collective effective dose from X-ray and NM procedures has increased 59% in 2008–2018, mainly due to the increase of collective doses of CT and interventional radiology. The collective dose from NM examinations is only 5% of the total collective dose from all radiological examinations. About 70% of the collective effective dose from X-ray examinations was caused by CT in 2018, while the proportion of CT procedures was only 16.5%. It is concluded that CT procedures are the major and increasing source of the collective dose from X-ray procedures.

While the use of new tissue weighting factors (ICRP 103) increases the population dose from plain radiography, it does not have effect on the population dose from CT examinations.

REFERENCES

1. European Commission. Council directive 2013/59/Euratom of 5 December 2013, laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom. Official Journal of the European Communities No L 13 57 (17 January 2014).
2. European Commission. European Guidance on Estimating Population Doses from Medical X-Ray Procedures. Radiation Protection No 154 (2008). Available from http://ec.europa.eu/energy/nuclear/radiation_protection/doc/publication/154.zip

3. European Commission. Medical Radiation Exposure of the European Population. Part 1/2. Radiation Protection No 180 (2014). Available from https://ec.europa.eu/energy/sites/ener/files/documents/RP180.pdf
4. Bly, R., Järvinen, H., Korpela, M. H., Tenkanen-Rautakoski, P. and Mäkinen, A. *Estimated collective effective dose to the population from X-ray and nuclear medicine examination in Finland*. Radiat. Prot. Dosim. **147**(1–2), 233–236 (2011).
5. Association of Finnish Local and Regional Authorities. *Radiologinen tutkimus- ja toimenpideluokitus*. (2018) (In Finnish).
6. Tapiovaara, M., Lakkisto, M. and Servomaa, A. PCXMC: A PC-Based Monte Carlo Program for Calculating Patient Doses in Medical X-Ray Examinations, report STUK-A139. (Helsinki: Finnish Centre for Radiation and Nuclear Safety) (1997).
7. International Commission on Radiation Protection (ICRP). *The Recommendations of the International Commission on Radiological Protection. ICRP Publication 103*. Annals of the ICRP **37**(2–4) (2007).
8. Hart, D. and Wall, B. F. Radiation Exposure of the UK Population from Medical and Dental X-ray Examinations. (National Radiological Protection Board (NRPB) Report NRPB-W4) (2002).
9. McParland, B. J. *A study of patient radiation doses in interventional radiological procedures*. Br. J. Radiol. **71**, 175–185 (1998).
10. Aroua, A., Trueb, P., Vader, J.-P., Valley, J.-F. and Verdun, F. R. *Exposure of the Swiss population by radiodiagnostics: 2003 review*. Health Phys. **92**(5), 442–448 (2007).
11. Rannikko, S., Karila, K. T. K. and Toivonen, M. Patient and Population Doses of X-ray Diagnostics in Finland. STUK-A 144. (Helsinki: Säteilyturvakeskus) (1997).
12. Järvinen, J. *et al. Contemporary radiation doses in interventional cardiology: a nationwide study of patient doses in Finland*. Radiat. Prot. Dosim. Apr **16**, 1–11 (2019) Epub ahead of print.
13. Lajunen, A. *Indication based diagnostic reference levels for adult CT examinations in Finland*. Radiat. Prot. Dosim. **165**(1–4), 95–97 (2015).
14. Shrimpton, P. C., Hillier, M. C., Lewis, M. A. and Dunn, M. Doses from Computed Tomography Examination in the UK-2003 Review. NRPB-W67. (Chilton: National Radiological Protection Board) (2005).
15. Deak, P. D., Smal, Y., Kalender, W. A. and Multisection, C. T. *Protocols: sex- and age-specific conversion factors used to determine effective dose from dose-length product*. Radiology **257**, 158–166 (2010).
16. International Commission on Radiation Protection (ICRP) and Addendum to ICRP Publication 53. *Radiation Dose to Patients from Radiopharmaceuticals. ICRP Publication 80*. Annals of the ICRP **28**(3) (1998).
17. International Commission on Radiation Protection (ICRP). *Radiation Dose to Patients from Radiopharmaceuticals: A Compendium of Current Information Related to Frequently Used Substances. ICRP Publication 128*. Annals of the ICRP **44**(2S) (2015).
18. International Commission on Radiation Protection (ICRP). *The Recommendations of the International Commission on Radiological Protection. ICRP Publication 60*. Annals of the ICRP **21**(1–3) (1991).
19. Radiation and Nuclear Safety Authority (STUK). Determination of the collective effective dose to population due to the use of radiation in health care (x-ray diagnostics and interventional radiology), Technical Report STUK-TR 21. (2016) (In Finnish).
20. Bly, R., Jahnen, A., Järvinen, H., Olerud, H., Vassileva, J. and Vogiatzi, S. *Collective effective dose in Europe from X-ray and nuclear medicine procedures*. Radiat. Prot. Dosim. **165**(1–4), 129–132 (2015).
21. National Council on Radiation Protection and Measurements. Medical Radiation Exposure of Patients in the United States (2019). Report No. 184 (2019).

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