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Patient doses in CT, dental cone beam CT and projection radiography in Finland, with emphasis on paediatric patients

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KILJUNEN Timo. Patient doses in CT, dental cone beam CT and projection radiography in Finland, with emphasis on paediatric patients. STUK-A232. Helsinki 2008. 62 pp. + apps. 66 pp.

Key words: patient dose, organ dose, effective dose, dosimetry, diagnostic imaging, CT, CBCT, radiography, paediatric, X-ray

Abstract

Diagnostic radiology represents the largest man-made contribution to population radiation doses in Europe. To be able to keep the diagnostic benefit versus radiation risk ratio as high as possible, it is important to understand the quantitative relationship between the patient radiation dose and the various factors which affect the dose, such as the scan parameters, scan mode, and patient size. Paediatric patients have a higher probability for late radiation effects, since longer life expectancy is combined with the higher radiation sensitivity of the developing organs. The experience with particular paediatric examinations may be very limited and paediatric acquisition protocols may not be optimised.

The purpose of this thesis was to enhance and compare different dosimetric protocols, to promote the establishment of the paediatric diagnostic reference levels (DRLs), and to provide new data on patient doses for optimisation purposes in computed tomography (with new applications for dental imaging) and in paediatric radiography.

Large variations in radiation exposure in paediatric skull, sinus, chest, pelvic and abdominal radiography examinations were discovered in patient dose surveys. There were variations between different hospitals and examination rooms, between different sized patients, and between imaging techniques; emphasising the need for harmonisation of the examination protocols.

For computed tomography, a correction coefficient, which takes individual patient size into account in patient dosimetry, was created. The presented patient size correction method can be used for both adult and paediatric purposes. Dental cone beam CT scanners provided adequate image quality for dentomaxillofacial examinations while delivering considerably smaller effective doses to patient compared to the multi slice CT. However, large dose differences between cone beam CT scanners were not explained by differences in image quality, which indicated the lack of optimisation.

For paediatric radiography, a graphical method was created for setting the diagnostic reference levels in chest examinations, and the DRLs were given as a function of patient projection thickness. Paediatric DRLs were also given for sinus radiography. The detailed information about the patient data, exposure parameters and procedures provided tools for reducing the patient doses in paediatric radiography. The mean tissue doses presented for paediatric radiography enabled future risk assessments to be done. The calculated effective doses can be used for comparing different diagnostic procedures, as well as for comparing the use of similar technologies and procedures in different hospitals and countries.

KILJUNEN Timo. Potilasannokset TT:ssa, hampaiston kartiokeila TT:ssa ja projektiokuvauksessa Suomessa painottuen lapsipotilaisiin. STUK-A232. Helsinki 2008, 62 s. + liitteet 66 s.

Avainsanat: potilasannos, kudosannos, efektiivinen annos, röntgenkuvaus, TT, kartiokeila TT, projektiokuvaus, lapset

Tiivistelmä

Diagnostisen röntgensäteilyn osuus ihmisen aiheuttamasta väestön keskimääräisestä säteilyannoksesta on kaikkein suurin. Jotta diagnostisen hyödyn ja säteilyhaitan välinen suhde voidaan pitää mahdollisimman suurena, on tärkeää ymmärtää kvantitatiivisesti potilaan säteilyannoksen ja siihen vaikuttavien tekijöiden, kuten kuvausarvojen, kuvausmenetelmien ja potilaiden kokojen välinen suhde. Lapsipotilailla on aikuisia suurempi riski säteilyn myöhäisiin haittavaikutuksiin, mikä on seurausta pitkästä odotettavissa olevasta eliniästä sekä kehittyvien elinten korkeasta säteilyherkkyydestä. Henkilökunnan kokemus tietyissä lasten tutkimuksissa voi olla rajallinen eikä lasten kuvausmenetelmiä välttämättä ole optimoitu.

Työn tarkoituksena oli kehittää ja vertailla eri annosmittausmenetelmiä tietokonetomografiatutkimuksissa (TT) ja lasten natiiviröntgentutkimuksissa, edistää lasten vertailutasojen käyttöönottoa sekä tuottaa uutta potilasannostietoa röntgentutkimusten optimointia varten.

Potilasannoskartoituksissa todettiin suuria vaihteluita kuvaustekniikoissa eri sairaaloiden, tutkimushuoneiden ja eri kokoisten potilaiden välillä. Tutkimustekniikoiden vaihtelusta aiheutuneet erot potilasannoksissa osoittivat tarvetta kuvausmenetelmien optimoinnille sekä kansallisella, että kansainvälisellä tasolla.

Tietokonetomografiatutkimuksia varten kehitettiin korjauskerroin, joka ottaa potilaan koon huomioon aikuisten ja lasten potilasannoksia määritettäessä. Tietokonetomografiatutkimuksissa lapset, naiset ja pienikokoiset potilaat absorboivat säteilyä suhteellisesti isokokoisia potilaita voimakkaammin. Hampaiston kuvantamisessa käytettävien rajoitetun kartiokeilan TT-laitteiden kuvanlaatu todettiin riittäväksi potilasannosten ollessa oleellisesti pienempiä kuin monileike-TT-laitteilla. Eri kartiokeila-TT-laitteiden potilasannoksissa oli kuitenkin suuria eroja kuvanlaadusta riippumatta, mikä osoitti tarvetta kuvaustekniikoiden jatkokehitykselle.

Lasten keuhkokuvauksia varten annettiin graafiset vertailutasot, joiden avulla sairaalat voivat suoraan verrata eri kokoisten potilaiden säteilyannoksia vertailutasoon. Vertailutasot annettiin myös lasten nenän sivuontelokuvauksia varten. Yksityiskohtaiset tiedot kerätystä aineistosta, kuvausarvoista ja -menetelmistä antoivat työkalut potilasannosten vähentämiseksi lasten natiiviröntgentutkimuksissa. Kudoksiin absorboituvien annosten määrittäminen mahdollistaa jatkossa potilaskohtaiset riskiarvioinnit. Määritettyjä efektiivisiä annoksia voidaan käyttää diagnostisten menetelmien ja kuvaustekniikoiden vertailuun eri sairaaloiden ja valtioiden välillä.

Contents

Original publications

I Kortesniemi M, Kiljunen T, Kangasmäki A. Radiation exposure in body computed tomography examinations of trauma patients. Physics in Medicine and Biology 2006; 51: 3269–3282.

II Kiljunen T, Järvinen H, Savolainen S. Diagnostic reference levels for thorax X-ray examinations of paediatric patients. The British Journal of Radiology 2007; 80: 452–459.

III Smans K, Vano E, Sanchez R, Schultz FW, Zoetelief J, Kiljunen T, Maccia C, Järvinen H, Bly R, Kosunen A, Faulkner K, Bosmans H. Results of a European survey on patient doses in paediatric radiology. Radiation Protection Dosimetry 2008; 129(1–3): 204–10.

IV Suomalainen A, Kiljunen T, Käser Y, Peltola J, Kortesniemi M. Dosimetry and image quality of four dental CBCT scanners compared with MSCT scanners. Dentomaxillofacial Radiology (in press).

V Kiljunen T, Tietäväinen A, Parviainen T, Viitala A, Kortesniemi M. Organ and effective doses in pediatric radiography – Patient dose survey in Finland. Acta Radiologica (in press).

List of abbreviations

AAPM	American Association of Physicists in Medicine
AP	Antero posterior
BEIR	Committee on the Biological Effects of Ionizing Radiations
CBCT	Cone beam CT
CEC	Commission of the European Communities
CI	Confidence interval
CNR	Contrast to noise ratio
CT	Computed tomography
CTDI	Computed tomography dose index
$CDTI_{vol}$	Volume weighted computed tomography dose index
D_T	Absorbed tissue dose
DAP	Dose-area product
DLP	Dose-length product
DLP_w	Weighted dose-length product
DRL	Diagnostic reference level
E	Effective dose
EC	European Commission
ERR	Excess relative risk
ESD	Entrance surface dose
FOV	Field of view
FSD	Focus skin distance
H_T	Equivalent dose
HU	Hounsfield unit
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
kerma	Kinetic energy released per unit mass
LAT	Lateral
LNT	Linear no threshold
MED	Medical exposure directive
MSCT	Multislice CT
MTF	Modulation transfer function
NCRP	National Council on Radiation Protection and Measurements (US)
NRPB	National Radiation Protection Board (UK)
PA	Postero anterior

PCXMC	PC based Monte Carlo program for calculating patient doses in medical X-ray examinations
PMMA	Polymethyl methacrylate
r_{eff}	Effective radius correction factor
RANDO	Radiation Analogue Dosimetry system
RSVP	Radiosurgery Verification Phantom
SENTINEL	Safety and Efficacy for New Techniques and Imaging using New Equipment to Support European Legislation (an EU project)
STUK	Radiation and Nuclear Safety Authority (Säteilyturvakeskus)
TLD	Thermoluminescent dosimeter
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
w_T	Tissue weighting factor

1 Introduction

The number and range of X-ray facilities and X-ray equipment is increasing rapidly and diagnostic radiology represents the largest man-made contribution to population doses in Europe (Mettler et al. 2008, Colgan et al. 2007, Muikku et al. 2007, Watson et al. 2005, EC 1997, Schibilla 1991). This observation applies to both developing and developed countries alike (UNSCEAR 2000). The European and national legislation concerning radiation protection states that the data concerning the risk caused to the patient by the use of radiation should be available, and special attention should be paid to paediatric imaging, fluoroscopy and computed tomography (EC 1997). In principle, the standard dose quantities registered from X-ray examinations should provide sufficient data for such radiation risk estimate. Patient dosimetry is regarded as an integral part of a quality assurance programme (Amis et al. 2007, IAEA 2007, ICRU 2005, STUK 2006a, AAPM 2002). The objective of dosimetry in radiological imaging is the quantification of radiation exposure within an approach to optimise the image quality to absorbed dose ratio. The objective of optimisation is to decrease the total patient dose in radiology and to reduce stochastic detriments, or cancer incidence, for the population without compromising diagnosis. Dosimetry also provides the means to avoid excessive doses that could imply a significant risk of induction of deterministic effects, or effects that cause straight detriments, such as skin burns. The dosimetric quantities and dosimetric protocols relevant in radiological imaging are those most closely related to the risks for the patient (IAEA 2007, ICRU 2005). Optimisation studies involve the assessment of the detriment associated with the radiation exposure, but also an estimation of the benefit the patient derives from the procedure by comparing the patient dose and corresponding image quality. The optimisation task is to maximise the benefit versus risk ratio for the diagnostic radiology procedure. The benefit risk ratio may be maximised by improving the benefit (such as an improved diagnosis) and by reducing the radiation risk by lowering the patient doses. Determination of the radiation exposure may be performed prospectively before the patient is scheduled to have an examination, measured during the examinations, or retrospectively after the examination has been performed, assuming that the dosimetric methods are well-known.

The guidance levels (or reference doses) for radiological imaging have been recommended by international organisations as a means of patient dose reduction (IAEA 1996, ICRP 1996a, EC 1996, CEC 1991). The Medical Exposure Directive (MED), 97/43/Euratom, of the European Commission (EC) (EC 1997) requires the member states to promote the establishment and use of diagnostic reference levels (DRL) for diagnostic examinations in radiology and nuclear medicine.

The Ministry of Social Affairs and Health takes into account the requirements of the MED in Finland (Ministry of Social Affairs and Health 2000). The DRLs are regarded as a tool for dose minimisation, and are based on the results of patient dose surveys. Diagnostic reference levels are expected not to be exceeded for standard procedures when good and normal practice regarding diagnostic and technical performance is applied (EC 1997). By using DRLs, it is possible to find those hospitals where radiation doses are exceptionally high and where practices may need to be improved. Various dosimetry quantities have been specified for DRL purposes. These include an entrance surface dose, dose-area product, computed tomography dose index, dose-length product and imaging time in fluoroscopy. Regular patient dose surveys in hospitals are integral to this process of dose minimisation. It is envisaged that patient dosimetry surveys will be performed to identify facilities where doses are in the upper quartile of the patient dose distribution. An audit of practices in the facility follows, with the intention of identifying dose reduction measures and improvements in techniques.

Computed tomography (CT) has grown into a major contributor to radiation dose obtained by patients in radiological studies. Currently, the CT studies may cover up to 17% of the procedures while already accounting for 60-75% of the diagnostic radiation dose received by the patients (Paterson and Frush 2007, Børretzen et al. 2007). From the early 1990s to the early 2000s, CT covered about 4% of procedures and 40% of the radiation dose (Shrimpton et al. 1991, Shrimpton and Edyvean 1998, Nagel 2002, Hart and Wall 2004, Karppinen and Järvinen 2006). Thus, the multi-slice CT (MSCT) scanners and their applications have contributed to the significant increase of dose in one particular modality. In Finland, the number of CT scanners was 15 per million inhabitants and ca. 50 000 CT examinations were done per million inhabitants per year (Rantanen 2007, Tenkanen-Rautakoski 2006). Both numbers were close to the mean value of developed countries, with the highest numbers in Japan and United States and the lowest in United Kingdom (Hall and Brenner 2008, UNSCEAR 2000). The increased utilization of CT (Figure 1) can be primarily attributed to two factors. MSCT and helical scanning are increasingly used in diagnostic imaging because of their efficiency as a diagnostic tool, providing simultaneously speed, high resolution and large coverage for diagnostic evaluation. Also, new applications of CT have expanded the role of CT into new types of clinical diagnoses, such as peripheral and cardiac angiography; virtual endoscopy, including bronchoscopy and colonoscopy; and multiplanar and volume reformats from isotropic data sets.

These are all now being performed using CT (Mahesh and Cody 2007, Einstein et al. 2007, Ouwendijk et al. 2005, Heyer et al. 2007, Kim et al. 2007, Elena 2008). Even though the benefits derived from CT examinations are considerable, the large number of CT scans performed each year, and the magnitude of the radiation doses from these examinations, has drawn attention to the potential risks from exposure to ionising radiation (Goldman 2008, Boland et al. 2008, Golding 2008, Brenner et al. 2001, Faulkner and Moores 1987). For example, the Alliance for radiation safety in paediatric imaging raises awareness in the imaging community on the need to adjust radiation dose in CT when children are imaged (www.imagegently.com). Despite similar CT scan parameters, both the image quality and the radiation dose delivered during CT procedures depend upon the patient size (Lee et al. 2008, Zatelli et al.2008, McNitt-Gray 2002, Frush 2002, Nickoloff 2002, Huda et al. 2001, Ware et al. 1999). The optimisation of CT exams requires a selection of scan factors that minimises the radiation dose to patients without having a significant impact upon the diagnostic accuracy of the examinations. Thus, it is important to understand the quantitative relationship between the patient radiation dose and the various factors which affect the dose. These include, for example, the scan parameters, scan mode, and patient size (Slovis 2002, Paterson et al. 2001, Donnelly et al. 2001).

Limited cone beam computed tomography (CBCT, μ-CT) scanners have been developed for dental and maxillo-facial imaging (Araki et al. 2004, Arai et al. 1999, Mozzo et al. 1998). Dental CBCT scanners use a fairly narrow cone-shaped X-ray beam instead of a wider fan or cone beam, which results in a scan range with a more restricted field of view (FOV) in the axial dimension than in traditional CT. The advantages of CBCT compared with MSCT are lower costs, smaller size of the scanner and lower radiation dose (Hashimoto et al. 2003). However, the image quality and radiation doses of CBCT scanners have not been thoroughly evaluated and compared to MSCT using the same method in both modalities. Thus the evaluation of the potential benefits and radiation burden that a specific examination causes to the patient has been difficult. The increasing use of CBCT examinations requires critical evaluation of these aspects.

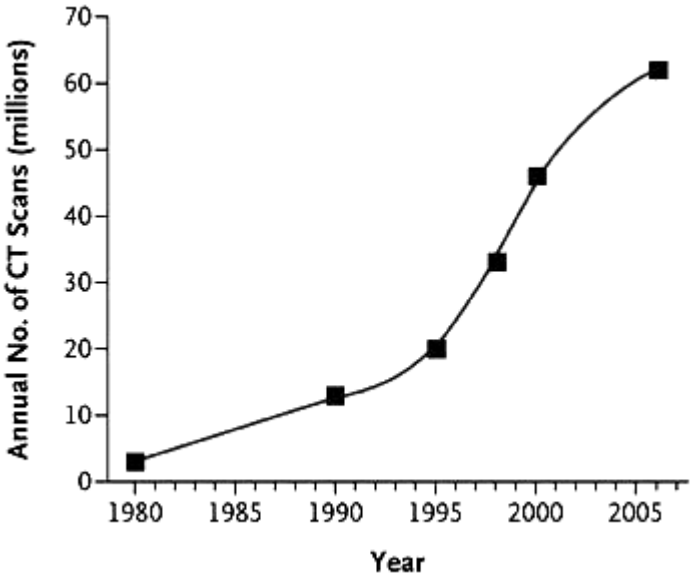

Figure 1. Estimated number of CT scans performed annually in United States (Brenner and Hall 2007).

Paediatric patients are a specific group regarding radiation protection in radiology because of the elevated risk for radiation detriments (UNSCEAR 2000). Paediatric patients have a higher probability for late radiation effects and they are assumed to be 2–3 times more radiation sensitive compared to adults, since their longer life expectancy time is combined with the higher radiation sensitivity of the developing organs, (UNSCEAR 2000, EC 1998, ICRP 1991). Also, there is evidence that low doses of ionising radiation to the brain in infancy influence cognitive abilities in adulthood at radiation doses equivalent to those of computed tomography (Hall et al. 2004, Huda et al. 2001). In Finland, about 4.1 million medical X-ray examinations are performed per year, of which close to 9% are for paediatric patients (Hakanen et al. 2003, Servomaa et al. 1997). The number of acquisitions and the dose per image should be reduced as much as possible. To be able to keep doses as low as reasonably achievable (ALARA principle), a fundamental knowledge of the factors concerning patient doses is needed. In study III, four facts that lead to relatively high patient doses in paediatric radiology were summarized:

- If a paediatric examination is performed once, the examination is most likely to be repeated. The mean number of repeated examinations for a neonate is 8–9 with maximum repetition number close to one hundred (Smans et al. 2008, Donadieu et al. 2006, Kettunen 2004). Cumulative organ doses and the effective dose per patient are usually neither known nor registered.

- The number of paediatric patients in a radiology department is usually small compared to adults. As a consequence, the experience with particular paediatric examinations may be very limited and paediatric acquisition protocols may not be optimised.
- Reference values for dose quantities of paediatric examinations can be retrieved from only a few publications (UNSCEAR 2000, Hart et al. 2000a, EC 1996). Notwithstanding the increased interest and legal requirements in the EC (Ministry of Social Affairs and Health 2000, EC 1997) for patient dosimetry and especially for paediatric patients, large multi-centre studies have not been performed in the recent past.
- Methods to limit the dose, such as the use of gonad protection or collimation, are not harmonised over Europe.

2 Patient dose and cancer risk

2.1 Linear no-threshold model

The basis for low dose radiation protection has been based on the linear no-threshold (LNT) theory of radiation carcinogenesis (ICRP 2008). According to the theory, a single radiation particle can initiate a cancer by hitting a single DNA molecule in the nucleus of a single human cell. The number of radiation particles is proportional to the dose, which is hence proportional to cancer initiation. Thus, when the number of damaged cells is decreased by a factor of 10, the expected biological response decreases by the same factor of 10; i.e., the response decreases linearly with decreasing dose. (Brenner et al. 2003, Cohen 2002)

Quantitative assessment of radiation carcinogenesis risks (or stochastic detriments) at low doses is based on the life span study (LSS) cohort of Hiroshima and Nagasaki atomic bomb survivors (Preston et al. 2007). The latest LSS data comprised of 17 448 primary cancers diagnosed from 1958 through 1998 among 105 427 cohort members. The data presented by Preston et al. were consistent with a linear dose-response at the low dose range. Linear dose-response extrapolated to low doses is presented in figure 2 (Pierce and Preston 2000). Another conclusion from the atomic bomb data is the fact that children are much more sensitive to radiation initiated carcinogenetic effects than older population. Children have more time to express a cancer than adults and children are inherently more sensitive to radiation because they have more dividing cells promoting the DNA mutagenesis (Brenner 2002). These facts give the shape for the sharply descending dose response function in figure 3, presented by the committee on the biological effects of ionising radiations (BEIR 2006), which is based on the atomic bomb data.

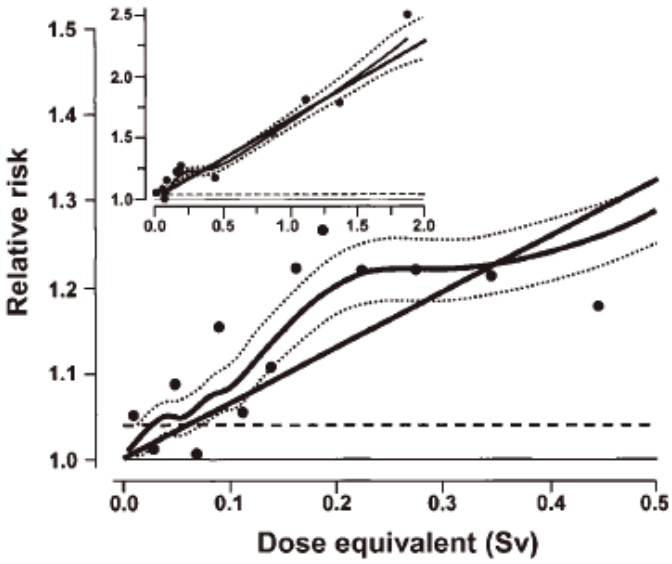

Figure 2. Relative cancer incidence as a function of dose (Pierce and Preston 2000). The dotted curves represent ± 1 standard error for the smoothed curve. The straight line is fitted over the whole dose range of 0–2 Sv (inset) standing for the LNT theory. The main figure is an expanded version of the low-dose region up to 0.5 Sv. Because of an apparent distinction between distal and proximal zero-dose cancer rates, the unity baseline corresponds to zero-dose survivors within 3 km of the bombs. The dashed line represents the alternative baseline if the distal survivors are not omitted (Hall and Brenner 2008).

The dependence between cancer incidence and dose has not been proved with statistical significance when the dose is lower than 6–40 mSv. For the atomic bomb survivors the estimated excess relative risk (ERR) was statistically significant ($p = 0.025$) in dose category of 5–125 mSv, with 34 mSv mean dose for the increase in solid cancer related mortality (Brenner et al. 2003). Cardis et al. (1995) and Muirhead et al. (1999) published results comprising of US, UK and Canadian nuclear workers with mean dose values of 30 and 40 mSv. The risk for leukaemia was significantly associated with cumulative external radiation dose ($p = 0.05$), but no excessive radiation risk was observed for other cancers. However, a larger 15 nation study (400 000 nuclear workers) was initiated and the results indicated a statistically significant ERR estimate of 0.97 (95% CI 0.14 to 1.97) per Sv, with a mean dose of 20 mSv (Cardis et al. 2005, 2007). The first analysis of solid cancer incidence in the Techa River cohort showed an ERR of 1.0 Gy^{-1} ($p = 0.004$, 95% CI 0.3; 1.9, mean dose 30 mGy) without any significant non-linearity in the dose response (Krestinina 2007). Also, statistically significant excess cancer incidence and mortality risks for solid cancers were found in the

Canadian studies, where the mean dose was 6.5 mSv (Ashmore et al. 1998, Sont et al. 2001).

Radiation risks are reviewed regularly by both national and international organisations (i.e. ICRP 2008, BEIR 2006, NCRP 2001, UNSCEAR 2000, NRPB 1995). The current consensus of these bodies is that for radiation protection purposes, the risk model in which the risk of radiation-induced cancer and hereditary disease is assumed to increase with increasing radiation dose without threshold is considered the most appropriate. Any increment of exposure above natural background levels will produce a linear increment of risk (Wall et al. 2006).

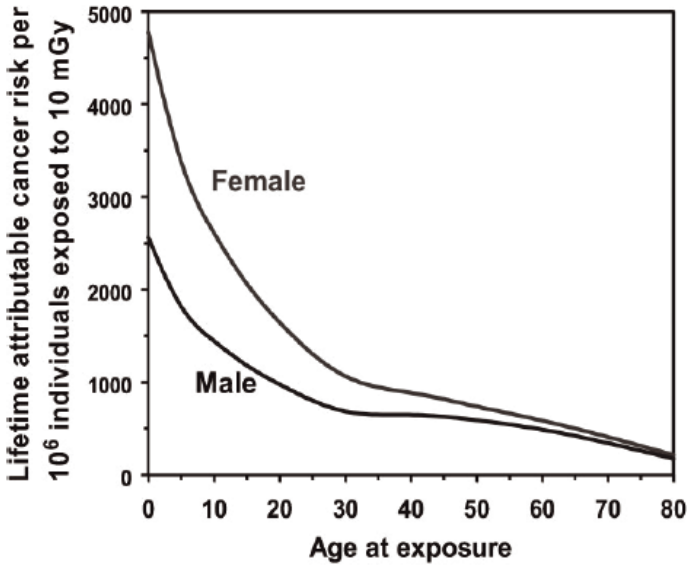

Figure 3. Estimated lifetime risk from a single small dose of radiation as a function of age at exposure (BEIR 2006). There is a strong decrease in radiation sensitivity with age. In addition, females are more sensitive compared to men. The higher risk for the younger age groups is not expressed until late in life (Preston et al. 2007, BEIR 2006).

3 Purpose and structure of the thesis

The purpose of this thesis was to enhance and compare different dosimetric protocols, to promote the establishment of the paediatric DRLs, and to provide new data on patient doses for optimisation purposes in diagnostic radiology. The thesis was focused on those radiological procedures, where the risks for radiation detriment are the largest. Potentially the most detrimental imaging modality, CT (with new applications for dental imaging), and the most risky patient group, paediatric patients, were included in the thesis. As fluoroscopy imaging is a complex technique and the evaluation of the protocols would require a thesis of its own, it was excluded from the thesis. The thesis was based on five original articles referred to in the text by their Roman numerals. The specific aims of the thesis work were:

- to present an individual method doing patient dose calculations in computed tomography, accounting for patient size for adult and paediatric patients in physical dose estimates and effective dose determinations (Study I)
- to compare the above method with standard dose quantities based on standard geometry (Study I)
- to determine the tissue and effective doses of dental cone beam CT scanners in comparison with multi slice CT scanners (Study IV)
- to evaluate the influence of the revised tissue weighting factors in cranial X-ray examinations (Study IV)
- to present a method that takes into account patient size when setting the paediatric diagnostic reference levels for chest X-ray examinations (Study II)
- to present preliminary European DRLs for paediatric X-ray examinations (Study III)
- to provide information on the paediatric examination protocols, entrance surface doses (ESD) and dose area products (DAP) for different aged children (Studies II, III, V)
- to determine organ doses and effective doses in paediatric projection radiography (Study V)
- to use patient dose data for optimisation of skull, paranasal sinus, chest, abdominal, and pelvic examinations (Study V).

- Article I:

Kortesniemi M, **Kiljunen T**, Kangasmäki A:
Radiation exposure in body computed tomography examinations of trauma patients.
Phys. Med. Biol. 2006; 51: 3269–3282.

The CT examination data from abdominal and thoracic scan series were collected from 36 trauma patients. The $CTDI_{vol}$, DLP_{w} and effective dose were determined, and the influence of patient size was applied as a correction factor to the calculated doses. The patient size was estimated from the patient weight by introducing a new correction factor for standard dose quantities. The correction was produced by analyzing the cross sectional areas and CT numbers from the axial images of abdominal and thoracic scan regions.

- Article II:

Kiljunen T, Järvinen H, Savolainen S:
Diagnostic reference levels for thorax X-ray examinations of paediatric patients.
Br. J. Radiol. 2007; 80: 452–459.

The paediatric dose data from earlier Finnish surveys were collected and patient dose measurements were executed in two regional hospitals. Different methods for setting the paediatric DRLs were considered and a new method was introduced for chest examinations.

- Article III:

Smans K, Vano E, Sanchez R, Schultz FW, Zoetelief J, **Kiljunen T**, Maccia C, Järvinen H, Bly R, Kosunen A, Faulkner K, Bosmans H:
Results of a European survey on patient doses in paediatric radiology.
Rad. Prot. Dosim. 2008; 129(1-3): 204–10.

A questionnaire was sent to the SENTINEL members asking for all available paediatric dose data, and procedure data for chest radiography of newborns. The data were gathered from 14 project partners from 13 European countries and preliminary DRLs were suggested to update the earlier values by European Commission.

- Article IV:

Suomalainen A, **Kiljunen T**, Käser Y, Peltola J, Kortesniemi M:
Dosimetry and image quality of four dental CBCT scanners compared with MSCT scanners.
Dentomaxillofacial Radiology (in press).

Tissue doses in dental CBCT examinations were measured using a tissue-equivalent anthropomorphic RANDO head phantom with thermoluminescence dosimeters (TLD). An RSVP head phantom with a specially designed cylindrical insert was used for comparison of image quality and absorbed dose. Image quality was evaluated in the form of contrast-to-noise ratio (CNR) and modulation transfer function (MTF).

- Article V:

Kiljunen T, Tietäväinen A, Parviainen T, Viitala A, Kortesniemi M:
Organ and effective doses in pediatric radiography – Patient dose survey in Finland.
Acta Radiologica (in press).

Paediatric examination data including patient information, examination parameters and specifications were registered in 24 Finnish hospitals. ESD and DAP were calculated retrospectively and/or DAP meters were used. Organ and effective doses were determined using a Monte Carlo programme PCXMC.

The author's contribution to the studies was: literature review and planning the method for the patient size corrections, performing the patient size analysis and producing the corrected dose quantities, and co-writing the article (I), constructing the study and performing the literature review; collecting, analysing and reporting the data, and writing the article (II), initiating the project together with SENTINEL participants, analysing and producing the Finnish paediatric dose data, co-analysing the European dose data and co-writing the article (III), planning the patient dose study, determining the tissue and effective doses, co-measuring the image quality and co-writing the article (IV), planning and executing the dose collection, analysing the data, performing the ESD and DAP calculations and most of the effective dose determinations, and writing the article (V). In addition, the author was drafting or revising and making the final approval of the versions of all the papers published as stated in the Vancouver Convention. These study results have not been used in other Ph.D. theses.

4 Materials and methods

4.1 Patient dose quantities

In radiological imaging, several quantities are used to quantify the magnitude of the exposure of the patient to ionising radiation (such as entrance surface dose, entrance surface air kerma, entrance skin dose, etc.). There is some ambiguity in their names and application in radiological procedures. The medical and radiobiological community currently relates the biological effects to the absorbed dose, which for medical X-rays and most common tissue equivalent materials is equal (within 5%) to another commonly used dose quantity, the kerma dose (ICRU 2005). In this thesis, the guidelines given by the International atomic energy agency (IAEA) and International commission on radiation units and measurements (ICRU) for assessing patient dose in diagnostic radiology are mainly used (IAEA 2007, ICRU 2005). The absorbed dose D is used as the primary dose quantity (Equation 1).

$$D = \frac{d\bar{\varepsilon}}{dm}, \tag{1}$$

where $d\bar{\varepsilon}$ is the mean energy imparted to matter of mass m (IAEA 2007). The special unit of absorbed dose is gray (Gy). Patient dose quantities and standard calculation methods have been thoroughly defined earlier (AAPM 2008, IAEA 2007, ICRU 2005, STUK 2004, Faulkner et al. 1999). The methods used in this thesis are introduced below.

4.2 The examination data

Studies I–III and V were based on the patient examination data collected in 1–24 hospitals. In study I, body CT examination data of 36 trauma patients from an emergency hospital were recorded by a questionnaire. In study II, the data consisted of published material collected previously by STUK (Servomaa et al. 2003, Parviainen et al. 2003), and new measurements were done in a central hospital and in a central health clinic. Total number of paediatric chest patients was 732. In study III, the members of the SENTINEL project were asked for all available paediatric dose data, except for CT. The data consisted of chest, abdominal and pelvic radiographic examinations received from 2–9 countries, varying between different examination and dose quantities used. In study V, a national paediatric patient dose survey was organized including four university

hospitals, 15 central hospitals and four large district hospitals. The data consisted of 72–1426 patients from chest, abdominal, pelvic, skull and sinus radiography examinations. In study IV, which was a phantom study, the patient dose and image quality were evaluated in dental CBCT examinations by choosing imaging parameters recommended by the manufacturer for four CBCT scanners and two MSCT scanners.

4.3 Patient dose in conventional radiography

Entrance surface dose (ESD) is the dose on the central X-ray beam axis at the point where the X-ray enters the patient or phantom, and it is mainly used in conventional radiography (IAEA 2007, ICRU 2005, STUK 2004). Dose-area product (DAP) is also mainly used in conventional radiography, but especially in fluoroscopy, as well al dental panoramic imaging (STUK 2004, Williams and Montgomery 2000, Faulkner et al. 1999). ESD can be measured using thermoluminescent (TL) dosimeters (IAEA 2007), calculated using tube output data and examination parameters (Equation 2), or it can be derived from DAP, if the field size A is known (Equation 3). Conversely, using Equation 3, DAP can be calculated if ESD and A are known. An easy way to determine DAP is using a DAP-meter. Also, many new X-ray devices have a calculatory DAP-display, which uses image parameters for an automatic DAP determination. ESD and DAP were determined in studies II, III and V by using Equations 2 and 3 or, when available, by using DAP-meters. In studies II and III, the tube outputs were measured by the author, whereas in study V the tube outputs were mainly reported by hospitals.

$$ESD = Y_{U,f} \cdot Q \cdot \left(\frac{FCD}{FSD} \right)^2 \cdot BSF \tag{2}$$

$$ESD = BSF \cdot \frac{DAP}{A} \tag{3}$$

$Y_{U,f}$ was the measured tube output depending on the tube voltage U and the filtration f used in imaging. Q was the product of tube current I and exposure time t, FCD was the focus–chamber distance used in X-ray output measurements, and FSD was the focus–skin distance used when imaging the patient. In study II, BSF (the backscattering factor) was determined individually for every patient. The values ranged for chest imaging between 1.33 and 1.46, depending mainly on the field size A at the focus skin distance, tube voltage and the filtration (Harrison 1983, Grosswendt 1990, Cranley et al. 1991). In studies III and V, the mean values presented by STUK were chosen (STUK 2004).

4.4 Patient dose in CT

For CT, skin dose and the dose at any specific point do not have the same significances as for conventional radiography, and special quantities are thus needed. The computed tomography dose index (CTDI, Equation 4) has been introduced as a fundamental dose quantity for multislice CT (Shope et al. 1981, AAPM 1990, EC 1999b, ICRU 2005, IAEA 2007). However, CT dose displays usually report volume weighted dose index ($CTDI_{vol}$, Equation 5), which represents the weighted mean dose absorbed to the imaged volume, as required in the International Electrotechnical Standard (IEC 60601). The CT doses are measured with a 10 cm pencil ionisation chamber inserted inside a cylindrical homogeneous PMMA (polymethyl methacrylate) phantom that is used to attenuate the primary beam and to generate scattered X-rays, simulating conditions when a patient is in the field (IAEA 2007). The diameter of the standard adult body phantom is 32 cm, and that of adult head phantom 16 cm. The CT head phantom is also used for paediatric imaging. In CT, dose distribution inside the phantom is heterogeneous so that the measured dose at the phantom surface is roughly double compared to the central dose (body phantom) (AAPM 2008). Thus, the central tissues, such as pancreas and kidneys, are much more vulnerable to radiation compared to conventional imaging in CT. The heterogeneity is reckoned with by measuring the dose in the centre and periphery positions of the phantom ($CTDI_{vol}$, Equation 5) and calculating the weighted dose value, which matches better with the real radiation distribution in the patient compared to the use of central or surface values only. Also, $CTDI_{vol}$ takes into account any gaps or overlaps between the X-ray beams from consecutive rotations of the X-ray source in axial and helical scan modes. Analogous to the DAP and ESD, the weighted dose-length product DLP_w, which can be calculated by multiplying $CTDI_{vol}$ with the total scan length L, is a better representative of the overall energy delivered by a given scan protocol, as the DLP_w reflects the total energy absorbed (and thus the potential biological effect) attributable to the complete scan acquisition. Thus, an abdomen-only CT exam might have the same $CTDI_{vol}$ as an abdominal/pelvic CT exam, but the latter exam would have a greater DLP_w, proportional to the greater z-extent of the scan volume (AAPM 2008). $CTDI_{vol}$ can be considered to be a technical dose quantity, whereas DLP is more practical in patient dosimetry.

$$CTDI_{100} = \frac{1}{nT}\int_{-5cm}^{5cm} D(z)dz \tag{4}$$

$$CTDI_{vol} = \frac{nT}{l} \cdot \frac{CTDI_{100,c} + 2CTDI_{100,p}}{3} \tag{5}$$

Subscript 100 (in Equation 4) refers to the length of the pencil ionisation chamber (10 cm) typically used for CT dosimetry, n is the number of simultaneously imaged slices, T is the collimated slice thickness, and l is the table increment per axial scan (or helical rotation). Subscripts *c, p* correspond to the central and periphery measurement sites used for the weighted CTDI value in the standard CT dosimetry phantom. In study I, the console display values $CTDI_{vol}$ were compared to the $CTDI_{100,air}$ based method, where additional scanner specific corrections introduced by Brix et al. (2003, 2004) were used in the modified version of CT-Expo v 1.4.2 programme using patient specific scan parameters as a data input (Stamm and Nagel 2004, Study I).

As the current dosimetry protocol of the AAPM (2008) uses only one standardized acrylic phantom representing the body of the adult patient, the different sizes and compositions of the patients are not reckoned with exactly. Individual patient dose can be estimated if the patient geometry and organ density are taken into account. This was done in study I by producing a correction factor (r_{eff}) for standard phantom thicknesses (Equation 6) and a dose scaling coefficient $C_{d,exam}$ (Equation 7, Huda et al. 2004, Nickoloff et al. 2003, Ware et al. 1999, Study I).

$$r_{eff} = \left(\frac{A_s}{\pi} \cdot \frac{HU_s + 1000}{HU_p + 1000} \right)^{\frac{1}{2}} \tag{6}$$

$$C_{d,exam} = \frac{A_c \cdot \exp\left(-\mu_c \cdot r_{eff,exam}\right) + 2A_p \cdot \exp\left(-\mu_p \cdot r_{eff,exam}\right)}{A_c \cdot \exp\left(-\mu_c \cdot r_{ref}\right) + 2A_p \cdot \exp\left(-\mu_p \cdot r_{ref}\right)} \tag{7}$$

In Equation 6, the mean cross-section areas (A_s) and mean CT numbers in Hounsfield units of the region scanned (HU_s) were determined for each patient. HU_p was the CT number of the phantom used. In Equation 7, A was the linear coefficient for the $CTDI_{100}$, μ the effective linear attenuation coefficient of the acrylic phantom and r_{ref} the reference phantom radius (16 cm for body region). The subscripts c and p (in A and μ) referred to centre and peripheral locations whereas the subscript *exam* (in C_d and r_{ref}) denoted the examined patient.

4.5 Patient dose in dental CBCT

In dental cone beam CT (CBCT) examinations, patient doses have been determined using DAP-meters, TLDs and CT dose indexes (Lofthag-Hansen et al. 2008, Suomalainen et al. 2008, Ludlow and Ivanovic 2008, Ludlow et al. 2006, Helmrot and Alm Carlsson 2005, Cohnen et al. 2002). The DAP based dosimetry

concept takes into account the total area irradiated, but represents only the surface dose. $CTDI_{vol}$ takes radiation distribution inside the patient roughly into account, whereas TLD measurements in the patient equivalent phantom enable the measurement of the radiation distribution more accurately, as well as the determination of the absorbed tissue doses. When the field of view (FOV) is small, the CTDI concept have been found to be erroneous, and the determination of the effective dose with DAP conversion factors have been found inaccurate (Lofthag-Hansen et al. 2008). Also, when the tube rotation is not full 360°, which may be the case in dental CBCT applications (Ludlow et al. 2008), the $CTDI_p$ values diverge. In study IV, thermoluminescent dosimeters (TLDs) were used for measuring the central axis dose inside the FOV and for determining the absorbed tissue doses in dental CBCT and MSCT examinations. Lithium borate ($Li_2B_4O_7$) TLDs and the Rados Dosacus RE-1/IR-1 TLD-reader/irradiator system (Rados Technology, Turku, Finland) were used for the measurements. A Sr-90 calibration source was used to correct the sensitivity fluctuations of individual dosimeters. The central axis doses were measured at the purpose-built image quality insert phantom, which was placed inside of the RSVP phantom (RSVP - Radiosurgery Verification Phantom, The Phantom Laboratory, Salem, NY, USA), providing an attenuation and scatter environment that resembled the human head.

4.6 Equivalent dose (H_T) and effective dose (E)

The probability of stochastic radiation effects has been found to depend on the magnitude of the absorbed dose, on the type and energy depositing the dose and on the tissue or organ irradiated (ICRP 1977, ICRP 1991, ICRP 2008, ICRU 2005). The equivalent dose (H_T) and effective dose (E) are defined as protection quantities, and they are used to specify exposure limits to ensure that the occurrence of stochastic health effects is kept below unacceptable levels, and that tissue reactions are avoided (Equation 8, ICRP 2008).

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R} \tag{8}$$

w_T is the tissue weighting factor for tissue or organ T, w_R the radiation weighting factor for radiation of type R, and $D_{T,R}$ is the absorbed dose to the tissue. In clinical radiology, the w_R is 1 for the used X-ray radiation, hence the absorbed tissue dose (Gy) equals numerically the equivalent dose (Sv). The current tissue weighting factors w_T and their development from ICRP 1977 are presented in Table 1. Effective dose (E) is intended to uniform the equivalent tissue doses to the whole body, which would have a similar risk of summarised health detriment to the exposure received by a reference person. It takes into account the probabilities

of radiation-induced cancer, a function of life lost, lethality, loss of quality of life, severe hereditary effects, and it is based on the detriment for a population of all ages and data averaged for the both sexes. E does not relate directly to the relative cancer risk of an individual, as there are known differences based on age and sex. For individual risk assessments the equivalent tissue dose should be used as a primary dose quantity (ICRP 2008). In medical practice, the use of E should be restricted to comparing the different health detriment to a reference patient for different types of medical examinations (ICRP 2008, Martin 2007).

Table I. The development of tissue weighting factors w_T for the effective dose determination (ICRP 2008).

Tissue	Tissue weighting factor		
	ICRP 1977	ICRP 1991	ICRP 2008
Bone surfaces	0.03	0.01	0.01
Bladder	-	0.05	0.04
Brain	-	-	0.01
Breast	0.15	0.05	0.12
Colon	-	0.12	0.12
Gonads	0.25	0.20	0.08
Liver	-	0.05	0.04
Lungs	0.12	0.12	0.12
Oesophagus	-	0.05	0.04
Red bone marrow	0.12	0.12	0.12
Salivary glands	-	-	0.01
Skin	-	0.01	0.01
Stomach	-	0.12	0.12
Thyroid	0.03	0.05	0.04
Remainder	0.30	0.05	0.12
Total*)	1.00	1.00	1.00

*) The list of the remainder tissues and different calculation methods for assessing the $D_{remainder}$ are presented in ICRP 2008 (current method), ICRP 1991 (ICRP 1994 and 1996b for a revised method to the calculation of the $D_{remainder}$), and ICRP 1977.

In practice, it is not pragmatic to conduct *in vivo* measurements of organ doses. Instead, D_T can be measured using appropriate physical models of human body that can be loaded with dosimeters, or organ doses can be determined using computer programmes that simulate radiation transport inside the mathematical or voxel phantom. As a coarse estimation of the effective dose, there are also Monte Carlo based conversion coefficients available for X-ray radiography and CT.

4.6.1 Effective dose by Monte Carlo simulations in conventional radiography

The Monte Carlo simulations have been found feasible for many applications in radiation physics (Smans et al. 2008, Andreo 1991). For patient dose calculations, the Monte Carlo method is used to determine the energy deposition of X-ray photons by creating a trajectory of virtual radiation particles by simulating random interactions between the particles and the medium (ICRU 2005, Lampinen 2000). In study V, the absorbed tissue doses and effective doses were determined in conventional paediatric radiology using the PCXMC 1.5 (STUK, Helsinki, Finland) – Monte Carlo simulation programme (Tapiovaara et al. 1997, Servomaa and Tapiovaara 1998). PCXMC 1.5 was based on mathematical anthropomorphic phantom model by Cristy (1980). The present software version PCXMC 2.0 is based on the updated phantom model by Cristy and Eckermann (1987) with further modifications in order to fulfil the new ICRP (2008) requirements (Tapiovaara and Siiskonen 2008). Focus-to-skin distance (FSD), field size and alignment determined the shape, position and orientation of the beam in the programme. The beam positioning was done using a graphical interface of the programme and the national and European guidelines for paediatric imaging (STUK 2008, EC 1996). An Excel-macro script was written to assist an automated input and output of the examination data between the PCXMC 1.5 and tabulation including the tube voltage and filtration that enabled individual patient dose determinations to be done. For each examination, the closest age-specific phantom model was chosen and the size of the phantom model was further adjusted according to patient's weight and height. ESD was the primary input dose indicator and PCXMC 1.5 reported distribution of the organ doses and the corresponding effective dose.

4.6.2 Effective dose by DLP and CTDI conversion coefficients in CT

In study I, scanner k_{CT} and scan region $f_{mean,st}$ specific conversion coefficient based on the CTDI value were used for the effective dose determinations (Brix et al. 2003, Shrimpton et al. 1991). Coarse coefficients based on the DLP provided by the EC (1999b) were also used as a comparison. Conversion factors for CT are discussed in detail by Huda et al. (2008).

Table II. Region specific ($f_{mean,st}$) and coarse (E_{DLP}) conversion factors used for the effective dose determinations. The region specific conversion factors determined for a standard CT scanner were used, with the scanner specific conversion k_{CT} (0.80 for GE lightspeed Qx/i) to the measured $CTDI_{air}$ value as specified in study I. E_{DLP} was used straight to the DLP_w value (Brix et al. 2003, EC 1999b).

Effective dose conversion factor (mSv/mGycm)	Chest	Abdomen	Pelvis
$f_{mean,st}$ (male/female)	0.0068/0.0088	0.0072/0.0104	0.0062/0.0112
E_{DLP}	0.017	0.015	0.019

4.6.3 Effective dose by tissue dose measurements with TLDs in CBCT

Physical dosimetry phantoms are designed to simulate the way in which the patient absorbs and scatters ionising radiation. In study IV, the anthropomorphic RANDO (Radiation Analogue Dosimetry system, Nuclear Associates, Hicksville, NY, USA) head phantom was used for tissue dose measurements with TLDs in dental CBCT examinations. The phantom was designed to match the tissue structure and attenuation environment of the human head, including bone, soft tissue and airways. The phantom has been designed for radiotherapy purposes, but the differences in massabsorbtion (μ_{ab}/ρ) coefficient for tissue equivalent materials allow the use of the RANDO in diagnostic radiology with an uncertainty less than 15%, depending on the anatomical sites (Shrimpton et al. 1981). The TLD chips were located at 26 phantom sites based on the method presented by Ludlow et al. (2006) to measure the absorbed dose to the tissues contributing to the effective dose. The absorbed dose to the eye lens was also measured in view of the known risk of deterministic detriments.

4.7 Diagnostic reference levels in paediatric radiology

Patient's size is an important factor in the level of dose received from X-ray examinations and as the variation of size is highest amongst children, the use of a single reference size (as suggested in EC 1996) may be impractical. A common way to report paediatric patient doses is to divide children into age groups (e.g. Azevedo et al. 2006, Gogos et al. 2003, Schultz et al. 1999). That, however, does not comprehensively solve the problem, because children within the same age group can still be of very different sizes (Hart et al. 2000b). In study II, patient dose in paediatric chest radiography examinations was evaluated comparing the standard deviations and the correlations between patient dose and the chosen size quantity. Patient thicknesses were measured at the central X-ray beam axis using a ruler, calculated from focus-skin distance and focus-detector distance

data, or measured from the X-ray image when both AP- and PA- projections were taken. The method presented by National Radiation Protection Board (NRPB), where normalization factors were established to normalize the doses of real patients to represent the doses of five standard-sized patients for whom the DRLs could be specified, was assessed, as well (Hart et al. 2000a,b). The third quartile (or 75%) values of patient doses were used to define DRL as suggested by the European commission (1999a). In order to set the national DRLs, there should be patient data collected from at least 20 national hospitals and the collection should include the most frequent examinations (Wall 2004). In order to fulfil those requirements, a national paediatric patient dose survey was established (Study V). An approach for revising paediatric DRLs on the European level (EC 1996) was done in Study III by collecting paediatric dose data that were available among the SENTINEL partners.

4.8 Image quality

Image quality was assessed in study IV using the contrast-to-noise ratio (CNR) and modulation transfer function (MTF). The CNR was evaluated using regions of interest (ROI) of Teflon and Perspex in the image quality insert phantom (Equation 9). The mean intensity value inside the ROIs was considered to be the signal and the noise was the arithmetic mean of the standard deviations in both ROIs.

$$CNR = \frac{CNR_{Teflon} - CNR_{Perspex}}{Noise} \tag{9}$$

The MTF was estimated also using the cylindrical Teflon region of the image quality phantom insert. Analysis was performed using a self-written Matlab (The MathWorks Inc., Natick, MA, USA) programme. The method to determine the MTF resembled the method presented by Li et al. (2007). MTF was calculated as the spatial frequency for which the MTF amounted to 10% of its maximum value.

5 Results

5.1 Size and gender depended patient doses in CT

The doses of trauma CT patients were studied in study I. Analyzing the cross-section areas and HU values, it was possible to determine a correction factor r_{eff}, which was used to correct the standard patient doses to represent individual differences. HU values were not dependent on patient weight whereas cross-sectional areas increased linearly in both thoracic and abdominal regions. In figure 4, the effective radius correction factor r_{eff} is presented as a function of patient weight. r_{eff} correlated linearly with patient weight ($p<0.001$) in both scan regions. The size of the standard phantom (r = 16 cm) corresponded to the patient weight of 116 kg. Only one of the 36 patients was bigger than that.

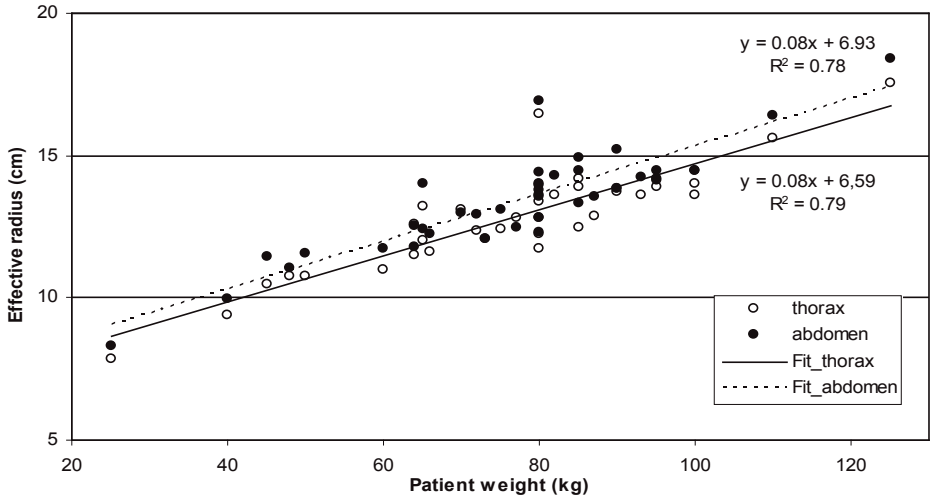

Figure 4. Effective radius of the standard dosimetric phantom as a function of patient weight for correction of the standard CT dose determination protocol. Effective radius was determined for 36 trauma CT patients by the evaluation of the mean CT numbers and cross section areas of the imaged slices in full body scan (Study I).

Patient doses, $CTDI_{vol}$, were determined using console display values, calculated based on the imaging parameters, and by using correction factor r_{eff} for both values. When applying correction for standard doses, $CTDI_{vol}$ were 35% and 9% higher than standard doses in chest and abdomen, respectively. The calculated $CTDI_{vol}$ values were 8% higher than console display values. The effective doses (ICRP 1991) were determined accordingly, using scanner specific corrections and coarse ImPACT/EU correction factors. The determined patient doses are presented in Table III. The difference between r_{eff} corrected whole body effective doses of females and males is presented in Figure 5.

Table III. The mean values of dose quantities determined with different dosimetric methods: calculation from imaging parameters (Calc), r_{eff}-corrected calculation from imaging parameters (Calc-corr), console display values (Cons), r_{eff} -corrected console display values (Cons-corr) and coarse correction coefficients (Coef) (Study I).

	Calc	Calc-corr	Cons	Cons-corr	Coef
Thorax					
$CTDI_{vol}$ (mGy)	15.2	20.4	14.1	18.9	
DLP_w (mGy·cm)	431	577	398	535	
E (mSv)	6.5	8.7	6.0	8.1	6.8
Abdomen					
$CTDI_{vol}$ (mGy)	18.5	20.1	17.1	18.6	
DLP_w (mGy·cm)	893	960	827	892	
E (mSv)	14.8	16.4	13.7	15.2	12.4

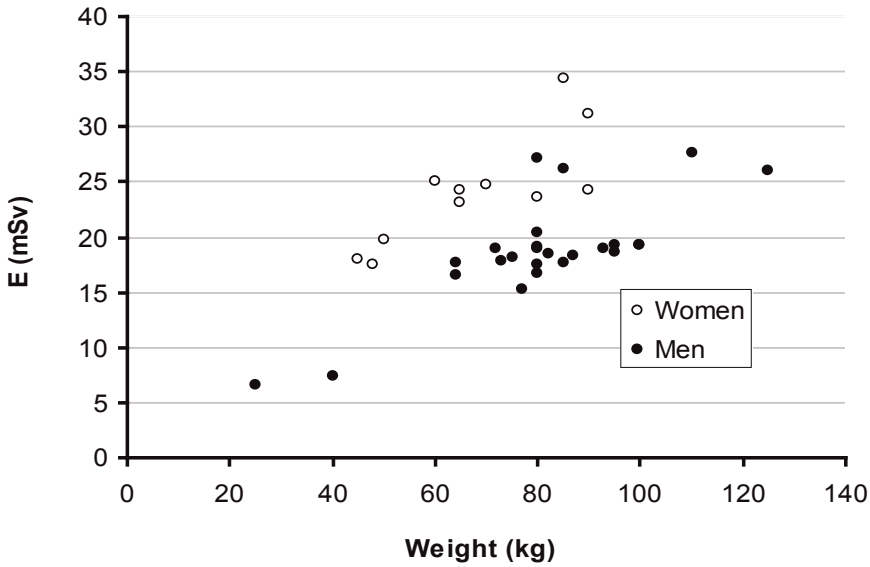

Figure 5. Effective patient doses calculated from individual scan parameters with the effective radius correction to women and men. Corrected effective dose to women was on average 66% higher compared to men; without correction, the difference was 29% (Study I)

5.2 Patient dose in dental cone beam CT compared to multi slice CT

The absorbed dose in dental CBCT was measured in two phantoms. The RSVP phantom provided accurate location of the TLDs on the central axis of the radiation beam with real scattering environment. The measured central axis doses could be compared directly with the image quality, which was measured in the same site of the image quality insert phantom (Study IV). The tissue dose measurements for the effective dose determinations were performed in the RANDO phantom. The absorbed central axis doses varied from 1 to 19 mGy for CBCT scanners, and from 24 to 33 mGy for MSCT scanners when standard imaging protocols were used. One CBCT scanner provided 2–5 times higher central axis dose than other CBCT scanners, while for image quality the differences were smaller (2.8–1.3 for contrast to noise ratio and 0.8–1.6 for modulation transfer function (10% value)).

The measured tissue doses in RANDO phantom corresponded to the central axis doses measurements by showing low values for three CBCT scanners, high values for two MSCT scanners and intermediate values for one CBCT scanner between them. The highest tissue doses were detected for salivary glands. The

effective doses were 1.3–53 times higher for the MSCT scanners compared to the CBCT scanners. The highest determined effective dose was 742 μSv, when calculation was performed using ICRP 1991 – tissue weighting factors. Using the new weighting factors, the determined effective doses were 1.9–2.6 times higher. The measured central axis doses with standard imaging protocols (Study IV) and the corresponding effective doses for four CBCT scanners and two MSCT scanners are presented in Figure 6.

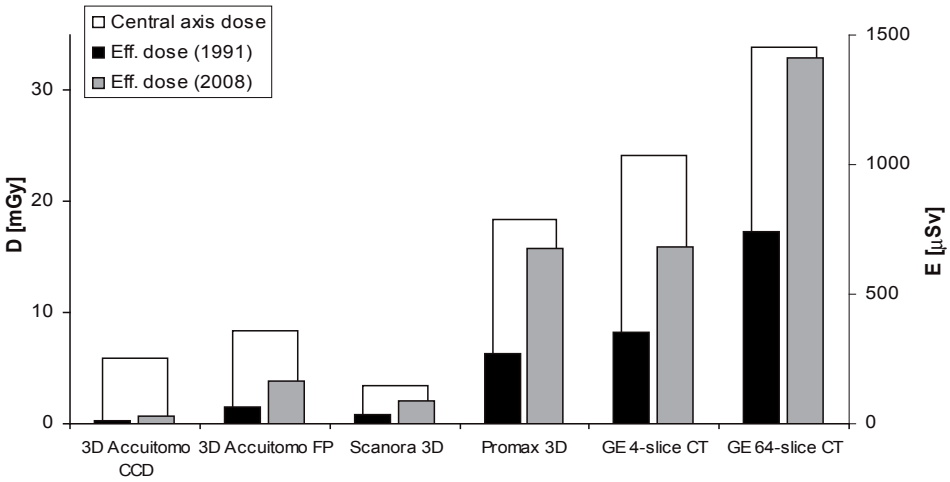

Figure 6. The results of the TLD measurements of four CBCT devices compared to two MSCT devices. The central axis dose is the absorbed dose measured at the central axis of the imaged region. Effective doses were determined using both ICRP 1991 and ICRP 2008 tissue weighting factors with standard imaging protocols (Study IV).

5.3 Paediatric patient doses

In study II, different methods for setting paediatric reference levels in conventional chest X-ray imaging were evaluated. In order to calculate the statistical patient dose values, the patients were divided into five groups. The method presented by the NRPB (UK) for determining the DRLs produced 12–40 percent additional uncertainty and was not found feasible for Finnish practice. The chest doses correlated exponentially with patient thickness in LAT ($r^2 = 0.99$) and AP (or PA) projections ($0.86 < r^2 \leq 0.90$). Diagnostic reference levels for paediatric chest imaging were given by STUK as functions of patient projection thicknesses (STUK 2006b). An example of applying the DRL is presented in Figure 7.

In both patient dose surveys (Studies III and V), paediatric dose data was collected from abdominal, pelvic and chest examinations. In addition, skull and sinus radiography doses were collected in the Finnish survey. In the Finnish

survey, the calculated mean values in chest examinations ranged between 3–180 μGy for ESD (AP or PA projection), and between 3–54 mGycm^2 for DAP, depending on the patient age group. These values were the lowest when compared to the European multi centre study, and thus much lower than the proposed new European DRLs, which ranged between 131–455 μGy (ESD) and 88–395 mGycm^2 (DAP) (Study III). In pelvic and abdominal examinations, the current European DRLs (EC 1996) were 5 and 9 times higher for newborns than corresponding mean values in the Finnish dose survey. In the age group of 5 years, the factors were 2 and 4. However, when compared to the new European survey, the Finnish doses in pelvic and abdominal examinations were similar or only slightly lower than the others. The data in both pelvic and abdominal examinations were lacking, so the new DRLs could not be proposed. In Finland, new DRLs were given for sinus examinations (2 mGy, 250 mGycm^2) (STUK 2006b). The preliminary European DRLs were proposed for chest radiography (Study III).

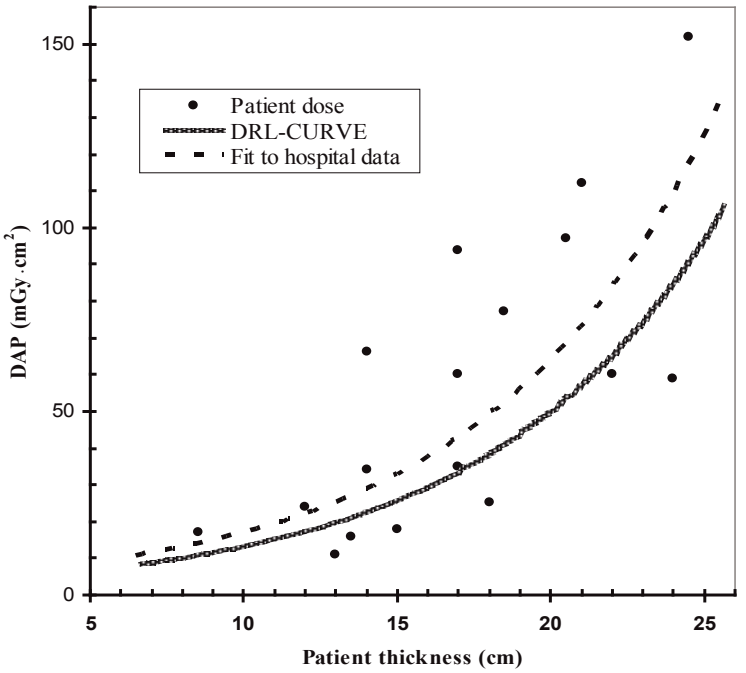

Figure 7. An example of comparing patient doses at a hospital with the DRL curve (solid line). Manually inserted patient doses are presented as solid circles, and the curve fitted to the patient dose data is presented as a dotted line. As there are more individual patient doses above the DRL curve, and the curve fit is above the DRL curve, the DRL is found to have been exceeded. The method was based on the Study II and the data for setting the DRL was based on the Study V. In chest radiography, paediatric DRLs were given by STUK in 2006 (STUK 2006b).

Based on the Finnish paediatric dose survey, the organ and effective patient doses were determined for skull, sinus, chest and abdominal radiography (Study V). In skull and sinus examinations the largest organ doses were calculated for skeleton and brain (60 µGy–300 µGy), whereas active bone marrow, thyroid, skin and muscles contributed the rest of the organ doses. The highest organ doses in abdominal examinations were calculated for liver (2010 µGy), upper large intestine (1466 µGy) and gall bladder (1433 µGy). In chest examinations, the highest organ doses were for lungs (166 µGy) and breast (169 µGy). All organ doses that contributed to the effective dose are listed in study V. Though mean ESD and DAP were higher in sinus examinations compared to chest, the effective doses were bigger in thoracic examinations, which corresponded to the amount of radiated organs sensitive to X-ray radiation. The biggest effective doses (ICRP 1990) were determined for abdominal examinations (18–483 µSv); for chest the doses ranged between 6 µSv and 48 µSv, while the sinus and skull doses were 6 µSv–14 µSv.

6 Discussion

6.1 Patient dose quantities, methods and uncertainties

6.1.1 Entrance surface dose (ESD) and dose-area product (DAP)

ESD and DAP values were determined for paediatric radiography in studies II, III and V. In study II, different sources of error were considered for projection radiography, when the entrance surface dose and dose-area product were calculated in retrospect using tube output measurements or DAP-meters with calibration. The estimated uncertainty of patient dose calculations was 19% for ESD measurements and, on average, 19% for DAP measurements. That corresponded to the International Electrotechnical (IEC 2000) standard, according to which the combined standard uncertainty of 25% should not be exceeded when using DAP-meters. In paediatric examinations, the accuracy requirement implicates that high resolution (0.1 mGy cm^2) is needed for DAP. Using DAP-meter with low resolution (e.g. 1.0 mGy cm^2) for measuring paediatric doses doubled the uncertainty (and exceeded the IEC standard) when compared to the high resolution meter (Study II). For paediatric patients, there is a tendency of aligning the imaging field outside of the body in order to see body outlines. That is not an acceptable imaging protocol (STUK 2008), and it overestimates the DAP value, as well. However, when a DAP meter is designed and calibrated for paediatric purposes, its use in patient dose measurements is reliable. The use of a DAP meter is convenient especially when performing the large number of patient dose measurements needed in patient dose surveys. Both ESD and DAP are practical dose quantities and their use is familiar for X-ray operators. ESD and DAP are the recommended quantities for diagnostic reference levels in X-ray imaging, in conventional dental imaging, and in fluoroscopy (DAP). ESD pays attention to the deterministic risk of skin detriments, which is especially the case in fluoroscopy (Geleijns and Wondergem 2005), while DAP takes beam area into account and corresponds better with the risk of the stochastic detriments.

6.1.2 Computed tomography dose index (CTDI) and dose-length product (DLP)

In study I, the uncertainty for computed tomography dose quantities ($CTDI_{vol}$, $CTDI_w$, DLP_w) was estimated to be 10–15%. There was also a specific uncertainty when considering the practical dose measurements. With the total collimated

beam width of 20 mm used in the standard dose measurements, the dose results based on the standard 100 mm pencil ionization chamber were underestimated (10%–40%) due to limited detection of scattered radiation (Boone 2007, Mori et al. 2005, Dixon 2003), but the induced error was acceptable. However, when newer MSCT scanners with potentially wider collimated beam widths are used, the appropriate handling of scattered radiation requires an updated dosimetric method, which has already been proposed in the literature (Perisinakis et al. 2007, Dixon 2003). The calculated $CTDI_{vol}$ were compared to the console-displayed values with an 8% concordance, which was an acceptable deviation considering the uncertainty of the dosimetric methods. The analysis of the cross-section areas and HU values for the effective radius correction factor r_{eff} was performed with ROI and threshold techniques in a self written Matlab programme. The linear dependence between r_{eff} and patient weight was mainly due to linear increase of cross-sectional area as a function of weight in both thoracic and abdominal scan regions. The coefficient in the model describing the effective radius as a function of patient weight agreed with the published data to a reasonable extent (Ware et al. 1999). The diameter-corrected and standard values of $CTDI_{vol}$ agreed well for the paediatric patients since the reference phantom diameter applied in paediatric body scans is 16 cm. Thus, the presented patient size correction method can be used for both adult and paediatric dose evaluation purposes. The relative errors of the effective patient radius determinations in the abdominal and thoracic regions were 3.7% and 3.5%, respectively. Analogous to the ESD and DAP in conventional imaging, CTDI and DLP are used as DRL quantities, and they have a wide range of usage in quality assurance and in optimisation process of CT protocols.

6.1.3 Thermoluminescent dosimeter (TLD) measurements

In study IV, TLDs were used for tissue dose measurements. The energy dependence of the TLD output was approximately 15% from 50 keV to 1 MeV (ICRU 2005) and the standard deviation of corrected TLD readings was 4%, when calibrated with a Sr-90 calibration source (Study IV). The expanded uncertainty (coverage factor of 2) was estimated to be 25% when small radiation doses were measured with $Li_2B_4O_7$ TL dosimeters (ICRU 2005, Zoetelief 2000). There are many factors influencing the TLD measurements and it is not a simple matter to give a specific figure for the resultant uncertainty (IAEA 2007). In study IV, tissue dose measurements were carried out inside the RANDO and RSVP phantoms, which caused uncertainty in the results as the TLD output is dependent also on the radiation geometry (Zoetelief 2000). However, the determined effective doses in study IV corresponded to the values published earlier for Accuitomo 3D CBCT

and GE 4-slice MSCT scanners (Study IV). Determining the tissue doses with TLDs was time-consuming and laborious when compared to the computational Monte Carlo methods, or using pre-evaluated conversion factors. However, for dental CT (or CBCT) imaging such conversion factors have been limitedly introduced (Lofthag-Hansen et al. 2008). Different conversion factors should be yielded for different dental regions and radiographic techniques taking new tissue weighting factors for granted.

6.1.4 Effective dose

Effective patient doses were determined in studies I, IV and V. E is not a measurable dose quantity. Instead it is derived by computation, so models and simulations are required in order to estimate the doses to individual tissues. Both mathematical and anthropomorphic phantoms have differences in the positions and sizes of the tissues, uncertainties in tissue properties, composition and radiation attenuation. ICRP now recommends voxel phantoms to be used for effective dose simulations (ICRP 2008). However, Smans et al. (2008) compared computational and voxel phantom models for paediatric purposes, and found good agreement between the two models. The differences were due to differences in phantoms and in equivalent fashion the alignment of the X-ray field. Also, the PCXMC version 1.5 has been evaluated against other simulation programmes with a reasonable agreement (Smans et al. 2008, Helmrot et al. 2007, Schultz et al. 2003, Schmidt et al. 2000, Tapiovaara et al. 1997). Random errors arise from differences between the phantom modelled and the reference patient. Uncertainty arises both when conversion factors are used and when tissue doses are measured e.g. with TLDs. As the weighting factors for effective dose determination are based on the A-bomb data with whole body irradiation, the evaluation and interpretation of effective dose is problematic when organs and tissues receive only partial exposure, or a very heterogeneous exposure, which especially is the case with diagnostic imaging (ICRP 2008). Martin (2007) has detailed the uncertainty in medical effective dose determinations. The uncertainty in E as a relative value for different types of medical exposure was ±40% for an 80–90% confidence limit. The revision of the weighting factors (ICRP 1991, 2008) has changed E by less than 20% for the majority of exposures of the trunk (Martin 2007). However, larger changes were involved for some examinations involving fewer organs, such as those in dental radiology (Study IV).

The effective dose is derived for workers and the general population, for which the age distribution can differ from the overall age distribution for the patients undergoing medical procedures using ionising radiation (ICRP 2008). Also, the risk for different age groups for uniform whole-body examinations varies

by a factor of 4–5 between children and the elderly (Pierce 2002). Thus, assessing the individual radiation risks for medical diagnosis when ionising radiation is used should be evaluated using mean absorbed doses for the individual tissues at risk, and combining these with the latest available age-, sex- and organ-specific risk coefficients for radiation-induced stochastic effects (Martin 2007). Effective dose should not be used for individual risk assessments. In diagnostic imaging, effective dose can be used for comparing the relative doses from different diagnostic procedures, and for comparing the use of similar technologies and procedures in different hospitals and countries. In addition, effective dose can be used for comparing the use of different technologies for the same medical examination, provided that the reference patient or patient populations are similar with regard to age and sex (Martin 2007).

In section 2, studies and organisations endorsing the linear no-threshold theory were covered. When compared to higher doses, the risks of low doses of radiation are likely to be lower, thus progressively larger epidemiological studies are required to quantify the risk to a useful degree of precision. For example, the study of nuclear workers had to be expanded to 400 000 cohort members until the influence of low dose radiation could be separated from background cancer incidence probability (Cardis et al. 2005, 2007). While the LNT theory has been found difficult to be proved with low doses, there has been an ongoing debate on other dose response models, led by the French National Academies of Science and of Medicine (Feinendegen et al. 2008, Mossman 2008, Leonard 2008, Tubiana et al. 2006 and 2007, Breckov 2006, etc.). According to them, the efficacy of the two guardians of the genome, DNA repair and programmed cell death, varies with dose and dose rate, and the use of LNT for assessing the risks of doses below 20 mSv is unjustified and should be discouraged (Tubiana et al. 2006). Also, interesting results have been presented based on the data of 10 000 cohort members of a Taiwanese radiation incident, which indicated that a dose rate of the order of 50 mSv per year would greatly reduce cancer mortality (Chen et al. 2004). The debate on low dose radiation risks will not be solved in the near future, and one has to rely on his/hers own ability to justify the profits and detriments of a medical radiation procedures. Although there are uncertainties in the quantity E, it still is the only general dose quantity which can link physically measurable dose quantities and risk of health detriment. In particular, E is practical during optimisation in radiology when comparing doses from different radiological techniques. Patients or referring physicians repeatedly ask for this information, not ESD, DAP, CDTI or DLP.

6.1.5 Patient data

Patient doses were determined in studies I–III and V based on the real patient data using actual imaging parameters for the individual patient dose detection, which enabled estimation of the average dose for a chosen population. Choosing the patient samples instead of phantoms, enabled to detect dose variations which are common in practice due to differences in patient size, variations in technique or skill between the individuals performing the examination, and differences in exposure factors that were locally selected. Such information could only be obtained by measuring the patient dose for a sample of patients, instead of phantom measurements in standard environment. Typically, in patient dose studies, it is important to select patients according to their anatomical parameters, such as weight and age. In this thesis it was intended to compare doses of different sized patients, so the large variation of patient sizes in the samples was desirable. However, depending on the study, the size of the sample for reliable statistical analysis varied. In study I, which was a methodological dosimetric study, the sample of 36 patients collected in one hospital was considered adequate, whereas sample sizes were as much as 20–50 times bigger in studies II–III and V, where Finnish or European dose levels were established. Large patient dose surveys may be problematic, since exact recording of the examination parameters is crucial. In a hospital, patient dose registration is usually done in addition to daily routine and may cause extra workload. Thus it is important to provide personnel with well-defined instructions and with simple questionnaires to make patient data collection as easy as possible. A possibility for online reporting and good availability for further assistance enables productive collaboration between the parties involved. When patient dose surveys are initiated, hospitals are often reminded of the legislative basis of patient dosimetry. However, the most efficient way to execute such surveys would be real co-operation by encouraging hospitals to participate in optimisation and in searching of a good practice in X-ray imaging. Furthermore, hospitals should receive direct feedback for their teamwork, and any results of the survey should be presented straight to hospitals.

6.2 Patient doses

6.2.1 Computed tomography and dental cone beam CT

Trauma patients were chosen for the computed tomography study (Study I) because of the widest scan area and thus potentially high patient doses. The determined doses ranged from 6 mSv to 35 mSv with a mean value of 20 mSv, proving that full body CT patients represent the highest dose group in diagnostic

radiology. The determined doses were slightly lower compared to other trauma CT studies (Winslow et al. 2008, Tien et al. 2007). The doses were in the proximity of statistically significant evidence of increased cancer risk (Chapter 2), and thus no extrapolation to low doses of LNT-model is needed when the radiation risk is considered (Hall 2008). It has been concluded that the use of CT is associated with a non-negligible lifetime attributable risk of cancer (Einstein et al. 2007). In USA, it is estimated that one third of CT examinations may have been done with inappropriate referrals (Brenner and Hall 2007). However, in an emergency room with multiply injured patients, CT has been considered critical to patient management, thus trauma CT is justified in most of the cases (Boland 2008). The determined trauma CT doses depended strongly on the patient size and gender. Differences in scan lengths led to differences in DLP values, as anticipated for different sized patients. However, the slice-specific doses independent of the scan length ($CTDI_{vol}$) within the same anatomical regions presented an inappropriate trend according to the patient size. The diameter-corrected mean effective dose from the whole examination of women was 65% higher than for men. That was due to two interrelated reasons: a smaller diameter and higher f_{mean} values of women in the trunk area compared to men. Thus, the need for optimisation of scan parameters for smaller patients is clearly emphasised, because this patient group includes mainly women with higher resultant exposures. The observed difference suggests that the use of standard dose quantities alone does not provide an adequate estimate of the patient doses that are delivered in CT. The use of patient size in dose estimation is therefore recommended in order to provide realistic dose quantities, to be used in referral evaluation, and to be registered for possible radiation risk calculations. This concerns especially children, women and smaller patients. In general, as CT contributes half of the diagnostic X-ray population dose and can be detrimental for individual patients, more concern should be drawn to the radiation protection of the CT.

Standard imaging methods in dental radiology include panoramic and intraoral radiographs, as well as other conventional tomographs and cephalograms. The use of CT in dentistry is limited, but the number of dental CBCT scanners is growing quickly. In standard dental imaging, patient doses are low (6 µSv for a panoramic image), which is 40 times less than the highest effective doses of the CBCT scanners examined (Study IV). When a CBCT examination is planned, it should be carefully considered whether the additional information contributes to the diagnosis and what its impact on the treatment of the patient is. Although CBCT imaging is a promising and already widely used diagnostic tool, definite recommendations on its clinical use are not available at this time. Large dose differences between CBCT scanners were detected without explaining the difference in image quality, which indicated the lack of optimisation. Further

studies are needed to evaluate low-dose MSCT and CBCT examinations, both of which are rapidly developing techniques in modern radiology.

6.2.2 Paediatric radiography

The most of the collected paediatric data in studies II, III and V consisted of chest X-ray examinations. That was logical as chest radiography is the most frequent examination performed for children; in Finland about 30% of all paediatric X-ray examinations are chest examinations (Servomaa et al. 1997). Patient dose in a single chest X-ray is relatively low, ranging from 6 µSv to 48 µSv (Study V), but the contribution to the total collective paediatric radiation exposure is significant due to the high imaging frequency compared to the CT. Contribution of different organs to the effective dose in different paediatric X-ray examinations was discussed in study V. In all examinations, there were large variations in imaging protocols and patient doses; thus emphasising the need for harmonisation. In sinus examinations, increasing focus to skin distance could have decreased the highest exposures by 30–60%. The effective doses in abdominal radiography were the highest of all. However, there was potential to improve optimisation by proper use of automatic exposure control and ensuring recommended imaging distances, especially in standing positions. In chest examinations, optimised projection (PA) should be utilized generally. The optimisation of pelvic radiography could have been improved by ensuring adequate tube voltage, imaging distance and utilizing the Cu filtration when available. In general, aligning the beam outside of the body overestimated the effective dose when DAP was used as the dosimetric source data.

6.2.3 Diagnostic reference levels

Compared to adults, the number of paediatric X-ray examinations is small. Therefore, it is difficult to collect enough patient data (at least 10 patients, Wall 2004) if the DRLs are given separately for each size group. A more practical method was presented in study II, where the paediatric chest DRLs were given as a function of patient thickness (STUK 2006b). When paediatric DRLs are presented as a curve, hospitals can compare their patient doses directly against the graph, and the need for a large number of patients is significantly reduced. According to an enquiry to university and central hospitals, the preliminary experiences in the application of the DRL curve were promising (Study II). As expected, using the DRL curve had simplified the procedure and reduced the workload when comparing patient doses with the DRLs. Of even more importance to the hospitals, the graphical illustration of patient doses had provided an

overview of the whole scale of the patient doses, which had then helped to choose an optimal imaging technique depending on patient size. In Finland, the paediatric DRLs were also given for sinus radiography (STUK 2006b). For sinus radiography, a single DRL was given, as the dependence of doses and patient size was considered small enough. Sinus radiography is not an acceptable imaging technique for children under the age of seven (STUK 2008).

7 Conclusions

In all studies included in this thesis, large variations in radiation exposure for a specific type of X-ray examination were discovered. There were variations between different hospitals and examination rooms, between different sized patients, and between imaging techniques; thus emphasising the need for harmonization of the examination protocols. A correction coefficient for CT, taking individual patient size into account, was created. The coefficient describing the effective radius as a function of patient weight agreed with the published data, and corrected values of $CTDI_{vol}$ agreed well also for the paediatric patients. The presented patient size correction method can be used for both adult and paediatric CT. Radiation absorption of children, women and smaller patients was found to be large compared to big patients in computed tomography examinations. Dental cone beam CT scanners provided adequate image quality for dentomaxillofacial examinations, while delivering considerably smaller effective doses to patients compared to the multi slice CT. Large dose differences between CBCT scanners were detected without explaining the difference in image quality, thus indicating the lack of optimisation. For paediatric radiography, a graphical method was found ideal for setting the diagnostic reference levels in chest examinations, and the DRLs were given as a function of patient projection thickness. Paediatric DRLs were also given for sinus radiography. In Finland, paediatric patient doses in chest examinations were much lower, whereas in abdominal and pelvic radiography the doses were similar or only slightly lower, when compared to the European multi-national study. The detailed information about the collected data, exposure parameters and procedures provided tools for reducing the patient doses in paediatric radiography. The mean tissue doses presented for paediatric radiography enabled future risk assessments to be done. The calculated effective doses can be used for comparing different diagnostic procedures, and for comparing the use of similar technologies and procedures in different hospitals and countries.

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