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Patient exposure monitoring and radiation qualities in two-dimensional digital x-ray imaging

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TOROI Paula. Patient exposure monitoring and radiation qualities in two-dimensional digital x-ray imaging. STUK-A239. Helsinki 2009. 53 pp. + apps. 74 pp.

Key words: dosimetry, radiation qualities, exposure monitoring, digital imaging, diagnostic radiology, mammography, calibration, dosemeter, x-ray energy spectra

Abstract

The methods for estimating patient exposure in x-ray imaging are based on the measurement of radiation incident on the patient. In digital imaging, the useful dose range of the detector is large and excessive doses may remain undetected. Therefore, real-time monitoring of radiation exposure is important. According to international recommendations, the measurement uncertainty should be lower than 7% (confidence level 95%).

The kerma-area product *(KAP)* is a measurement quantity used for monitoring patient exposure to radiation. A field KAP meter is typically attached to an x-ray device, and it is important to recognize the effect of this measurement geometry on the response of the meter. In a tandem calibration method, introduced in this study, a field KAP meter is used in its clinical position and calibration is performed with a reference KAP meter. This method provides a practical way to calibrate field KAP meters. However, the reference KAP meters require comprehensive calibration.

In the calibration laboratory it is recommended to use standard radiation qualities. These qualities do not entirely correspond to the large range of clinical radiation qualities. In this work, the energy dependence of the response of different KAP meter types was examined. According to our findings, the recommended accuracy in *KAP* measurements is difficult to achieve with conventional KAP meters because of their strong energy dependence. The energy dependence of the response of a novel large KAP meter was found out to be much lower than with a conventional KAP meter. The accuracy of the tandem method can be improved by using this meter type as a reference meter.

A KAP meter cannot be used to determine the radiation exposure of patients in mammography, in which part of the radiation beam is always aimed directly at the detector without attenuation produced by the tissue. This work assessed whether pixel values from this detector area could be used to monitor the

radiation beam incident on the patient. The results were congruent with the tube output calculation, which is the method generally used for this purpose. The recommended accuracy can be achieved with the studied method.

New optimization of radiation qualities and dose level is needed when other detector types are introduced. In this work, the optimal selections were examined with one direct digital detector type. For this device, the use of radiation qualities with higher energies was recommended and appropriate image quality was achieved by increasing the low dose level of the system.

TOROI Paula. Potilaan säteilyaltistuksen monitorointi ja säteilylaadut kaksiulotteisessa digitaalisessa röntgenkuvantamisessa. STUK-A239. Helsinki 2009, 53 s. + liitteet 74 s.

Avainsanat: dosimetria, säteilylaadut, säteilyaltistuksen monitorointi, digitaalinen kuvantaminen, diagnostinen radiologia, mammografia, kalibrointi, annosmittari, röntgen energiaspektri

Tiivistelmä

Menetelmät potilaan röntgenkuvauksesta saaman säteilyaltistuksen arviointiin perustuvat potilaaseen kohdistuvan säteilyn mittaamiseen. Digitaalisessa kuvantamisessa ilmaisimelle sopiva annosalue on laaja ja liian suuret annokset saattavat jäädä huomaamatta. Sen vuoksi reaaliaikainen säteilyaltistuksen monitorointi on tärkeää. Kansainvälisten suositusten mukaisesti mittausepävarmuuden pitäisi olla alle 7% (luottamustaso 95%).

Mittaussuuretta kerman ja pinta-alan tulo *(KAP)* käytetään potilaan säteilyaltistuksen monitorointiin. KAP-kenttämittari on tyypillisesti kiinnitettynä röntgenlaitteeseen ja on tärkeää huomioida mittausgeometrian vaikutus mittarin vasteeseen. Tässä työssä esitetyssä tandem-kalibrointi -menetelmässä, KAP-kenttämittaria käytetään sen omalla paikallaan ja kalibrointi suoritetaan KAP-vertailumittarin avulla. Tämä menetelmä tarjoaa käytännöllisen tavan kalibroida KAP-kenttämittareita. Kuitenkin, KAP-vertailumittarilla pitää olla kattava kalibrointi.

Kalibrointilaboratoriossa suositellaan käytettävän standardin mukaisia säteilylaatuja. Nämä laadut eivät täysin vastaa kliinisten säteilylaatujen laajaa valikoimaa. Tässä työssä tutkittiin eri KAP-mittarityyppien vasteiden energiariippuvuutta. Tutkimuksemme perusteella perinteisillä KAP-mittareilla suositeltu tarkkuus on vaikea saavuttaa *KAP*-mittauksissa johtuen niiden vahvasta energiariippuvuudesta. Uudentyyppisen ison KAP-mittarin energiariippuvuuden todettiin olevan paljon pienempi kuin tavallisilla KAP-mittareilla. Tandem-menetelmän tarkkuutta voidaan parantaa käyttämällä tämän tyyppistä mittaria vertailumittarina.

KAP-mittaria ei voida käyttää potilaan säteilyaltistuksen arviointiin mammografiassa. Mammografiassa osa säteilykeilasta osuu suoraan ilmaisimelle ilman kudoksen aiheuttamaa vaimennusta. Tässä työssä tutkittiin voisiko tältä alueelta ilmasimelta saatua pikselilukemaa käyttää potilaaseen kohdistuvan

säteilykeilan monitorointiin. Tulokset olivat yhteneviä yleisesti käytetyn säteilytuottolaskennan kanssa ja suositeltu tarkkuus voidaan saavuttaa tutkitulla menetelmällä.

Säteilylaatujen ja annostason uusi optimointi on tarpeen, kun otetaan käyttöön uusia ilmaisintyyppejä. Tässä työssä optimaalisia vaihtoehtoja tutkittiin yhdellä taulukuvailmaisinperusteisella digitaalisella mammografialaitteella. Tällä laitteella suurempienergisten säteilylaatujen käyttöä suositeltiin ja riittävä kuvanlaatu saavutettiin nostamalla laitteen matalaa annostasoa.

Contents

Original publications

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

I Toroi P, Komppa T, Kosunen A. A tandem calibration method for kerma-area product meters. Phys. Med. Biol. 2008; 53: 4941–4958.

II Toroi P, Komppa T, Kosunen A, Tapiovaara M. Effects of radiation quality on the calibration of kerma-area product meters in x-ray beams. Phys. Med. Biol. 2008; 53: 5207–5221.

III Toroi P, Kosunen A. The energy dependence of the response of a patient dose calibrator, Phys. Med. Biol. 2009; 54: N151–N156.

IV Toroi P, Nieminen M, Tenkanen-Rautakoski P, Varjonen M. Determining air kerma from pixel values in digital mammography. Phys. Med. Biol. 2009; 54: 3865–3879.

V Toroi P, Zanca F, Young KC, van Ongeval C, Marchal G, Bosmans H. Experimental investigation on the choice of the tungsten/rhodium anode/filter combination for an amorphous selenium-based digital mammography system. European Radiology 2007; 17 (9): 2368–2375.

The author took part in planning all the studies and mainly carried out the measurements and analysed 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. theses.

List of abbreviations

AAPM	American Association of Physicists in Medicine
ALARA	As low as reasonably achievable
CEC	Commission of the European Communities
CNR	Contrast-to-noise ratio
CR	Computed radiography
DAP	Dose-area product
DR	Direct digital system
DRL	Diagnostic reference level
EC	European Commission
EI	Exposure index
HVL	Half-value layer
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiation Protection
ICRU	International Commission on Radiation Units and Measurements
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
KAP, P_{KA}	Kerma-area product
Kerma, K	Kinetic energy released per unit mass
MED	Medical Exposure Directive
MGD	Mean glandular dose
NRPB	National Radiation Protection Board (UK)
PDC	Patient dose calibrator (Radcal)
PMMA	Polymethyl methacrylate
PSDL	Primary Standard Dosimetry Laboratory
PV	Pixel value
RQR	Name of the set of standard radiation qualities (IEC 2005)
SDNR	Signal difference-to-noise ratio = CNR
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 in Finland
SSDL	Secondary Standard Dosimetry Laboratory
STM	Ministry of Social Affairs and Health in Finland
TLD	Thermoluminescent dosimeter

Aims of the study

The main purpose of the work presented in this thesis was to assess the possibilities to improve the accuracy and reliability of patient exposure monitoring in two-dimensional x-ray imaging. Measurement uncertainties were evaluated to conclude whether the internationally recommended accuracy levels can be achieved in exposure measurements with monitoring dosemeters. Improved calibration methods for the dosemeters were introduced, with particular attention paid to the differences in radiation qualities used in calibration and in the actual measurement. The effect of the transition from film-screen to digital imaging on radiation qualities was studied in relation to exposure levels in digital mammography.

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

1) present a new method for cross calibration of kerma-area product (KAP) meters, where another KAP meter is used as a reference instrument (studies I, II, III);

2) examine the energy dependence of the response of conventional and novel type KAP meters and evaluate the inaccuracies due to differences in radiation qualities used in a calibration laboratory and in the clinical situation (studies II, III); and

3) study the effect of using unconventional radiation qualities on exposure levels and introduce an exposure monitoring method for the direct digital mammography system (studies IV, V).

- Study I

Toroi P, Komppa T, Kosunen A.
A tandem calibration method for kerma-area product meters
Phys. Med. Biol. 2008

The kerma-area product (*KAP*) is used in medical x-ray examinations to monitor the radiation exposure of patients. As an effort to improve the calibration procedures for KAP meters, a tandem calibration method was developed. In this method, the field KAP meter is used in its clinical position and the reference value is measured simultaneously at a larger distance in the beam with a reference KAP meter. In this work the tandem method was described, demonstrated and compared with other methods. Uncertainties were estimated and compared with the recommended accuracy.

- Study II

Toroi P, Komppa T, Kosunen A, Tapiovaara M.
Effects of radiation quality on the calibration of kerma-area product meters in x-ray beams
Phys. Med. Biol. 2008

The calibration coefficients of KAP meters depend on the energy spectrum (radiation quality) of the x-ray beam. This dependence was examined by measuring the calibration coefficients for several radiation qualities in the range of filtrations and tube voltages generally used in medical x-ray imaging and in calibration laboratories. The accuracy of *KAP* measurements was investigated with respect to calibration coefficients and procedures needed in clinical practice.

- Study III

Toroi P, Kosunen A.
The energy dependence of the response of a patient dose calibrator
Note in Phys. Med. Biol. 2009

The energy dependence of response of a novel large KAP meter type (patient dose calibrator, PDC) was examined by measuring the calibration coefficients for several standard and clinical radiation qualities. The uncertainty related to energy dependence was estimated and compared with the response of traditional meters.

- Study IV

Toroi P, Nieminen M, Tenkanen-Rautakoski P, Varjonen M.
Determining air kerma from pixel values in digital mammography
Phys. Med. Biol. 2009

The use of direct digital detector elements for monitoring patient exposure in digital mammography was examined. The response of pixel values from the detector elements in the unattenuated primary beam area was investigated within a large exposure and energy range for two detector types. Using these calibration results, air kerma was measured from clinical patient images and compared with the tube output calculation, which is the general method for exposure estimation.

- Study V

Toroi P, Zanca F, Young KC, van Ongeval C, Marchal G, Bosmans H.
Experimental investigation on the choice of the tungsten/rhodium anode/filter combination for an amorphous selenium-based digital mammography system
Eur. Rad. 2007

The use of unconventional radiation qualities with higher energies for a direct digital mammography system was investigated. An optimization study was performed with a large range of radiation qualities and breast thicknesses. The use of the tungsten/rhodium anode/filter combination was under specific interest.

1 Introduction

The radiation dose from individual medical x-ray imaging system needs to be measured for different purposes, including quality control, optimization and the estimation of patient exposure. The importance of patient exposure estimation was highlighted by the Medical Exposure Directive (MED) 97/43/ Euratom (EC 1997) and taken into Finnish legislation in 2000 (STM 2000). Based on the recommendations of the European Commission (EC, 1997), patient exposures should be compared to an achievable level, such as the diagnostic reference level (DRL). Patient exposure levels have been recorded and compared in international studies (e.g. Vano et al. 2008a) and in Finland (e.g. Rannikko et al. 1997, Karppinen and Järvinen 2006, Kiljunen 2008). The risk for the patient can be estimated from the measurable quantities using simulation models (e.g. Lampinen 2000, Tapiovaara and Siiskonen 2008) or using calculated conversion factors (ICRU 2005, ICRP 2007). However, the basis for comparable and accurate results is a uniform and accurate measurement method and the use of properly calibrated dosemeters.

Standardized calibration and measurement methods are important to achieve accurate and comparable results. For dosimetry in diagnostic radiology, the International Atomic Energy Agency (IAEA) has provided guidelines in the International Code of Practice (2007). Other guidelines have been given, for example, by the ICRU (2005) and STUK (2004). In the diagnostic use of x-rays, uncertainties of 7% (confidence level of 95%, coverage factor $k = 2$) or lower are recommended for exposure measurements (Wagner et al. 1992, ICRU 2005, IAEA 2007). Even though there are large uncertainties in estimating the health effects of radiation, it is generally known that even a 10% reduction in the dose level is essential for optimization purposes, which is why the goal for measurement accuracy is set so high (IAEA 2007).

In past, the main interest in medical x-ray imaging dosimetry was in estimating the radiation exposure of the staff. Subsequently, the determination of patient exposure has become general and obligatory, but traditions for patient dosimetry are still under development. The dosemeters used for exposure measurements are typically adjusted by the manufacturer and set to display a proper value with one measurement geometry and radiation spectrum. To achieve comparable results, the calibration of these dosemeters should be traceable to international standards. The electrical adjustments made by manufacturers may lack this requirement if they are not authorized to provide such a service by the national metrology body.

Standard radiation qualities are recommended and generally used in calibration laboratories for calibrating diagnostic dosemeters (IEC 2005, ICRU

2005, IAEA 2007). However, these do not completely cover the large range of radiation qualities used in clinical situations (e.g. Lin 2007, Vano et al. 2008c). A proper radiation quality specification is needed for the step between calibration and clinical radiation qualities. The x-ray energy spectrum is continuous and it is difficult to describe it properly with one parameter. The half-value layer (*HVL*) is generally used for this purpose, but for dosemeters with a strong energy dependence it may be inadequate. For example, the response of a kerma-area product (KAP) meter is known to have strong energy dependence (Larsson et al. 1996, 1998, 2006, Bednarek and Rudin 2000, Malusek et al. 2007).

In film-screen radiography, overexposure is detected by excessively dark film. In digital imaging, the useful dose range is expanded due to the large dynamic range of digital detectors, and high exposures may thus remain undetected. This emphasizes the need for real-time exposure monitoring during examinations. Especially with fluoroscopy and interventional systems, the exposures are large and the duration of irradiation is determined by the user, and it is important that a real-time estimation of the patient exposure is available (Cusma et al. 1999). Modern x-ray units are often equipped with a fixed or removable KAP meter or a display of the computed *KAP* value based on the x-ray tube output and field size settings. KAP meters are commonly used for monitoring patient exposure in general radiology and especially for interventional radiology, in which long exposures are performed. The need for KAP meter calibrations is evident (Larsson et al. 1996, 1998, 2006, Jankowski 2008, Hetland 2009). KAP meters are often calibrated and adjusted by the manufacturer and the calibration is not traceable to international standards. It is generally recommended that a KAP meter should be calibrated using the same x-ray unit and irradiation geometry as used with patients, mainly because of the equipment-specific characteristics of extra-focal and stray radiation (Shrimpton and Wall 1982, ICRU 2005). In some cases, meters are attached to the system and it may even be impossible for the user to send it for calibration.

The *KAP* of an x-ray beam is the surface integral of air kerma over the area of the entire beam in a plane perpendicular to the beam axis (ICRU 2005). Generally, field calibrations of KAP meters are performed with the beam-area method; *KAP* reference values for calibration are determined by approximating the surface integral by the product of the nominal area of the x-ray field and the air kerma measured at the centre of the field (Shrimpton and Wall 1982, NRPB 1992, Larsson et al. 1996 and 1998, ICRU 2005, IAEA 2007). This method has the limitation of the dependence of resulting calibration coefficients on the non-uniformities of the x-ray beam. Other sources of uncertainty include the measurements of field size and the location of the planes of air kerma and field size determination (Larsson et al. 1996, 1998, 2006, Malusek et al. 2007). The accuracy of calibration could be improved by measuring the reference *KAP* value directly according to the definition, thus avoiding the problems arising from the non-uniformities of the x-ray field. Larsson et al. (1996) used TLDs to measure the surface integral, but this method is quite laborious.

Because the difference between conventional and digital imaging is on the detector side, not in the production of radiation, the methods for exposure measurement will not necessary change. For example, KAP meters can be used in the same way in both systems. However, KAP meters cannot be used in mammography because of their higher useful energy range and the attenuation and filtration effect of the KAP chamber (IEC 2000). Mammography is used in screening a large group of healthy women and it is very important to capture possible inappropriate exposure levels or malfunctions of the system at an early stage. The digital output may offer new possibilities for using pixel values from a digital detector in dose calculation and monitoring (Floyd et al. 1990, Tucker and Rezentes 1997, Ariga et al. 2007, Kauppinen 2008, Vano et al. 2008b). In mammography, the image detector area is commonly only partly covered by tissue and the incident air kerma could be monitored by using pixel values from the detector elements in the unattenuated primary beam area. An exposure index (EI) or other relationship between pixel values and the dose on the detector is usually examined with one radiation quality and under some additional attenuation (IEC 2007, 2008, EC 2006). However, if pixel values are used for exposure estimation, the response function of the detector should be studied as a function of energy.

The radiation qualities and exposure levels for film-screen imaging have been optimized during many years of experience. With new digital systems, the detector types and their responses are different and new optimization is therefore needed. The manufacturer should perform the primary adjustment of optimal radiation qualities and exposure levels. In many cases, new technologies have been rapidly taken in use and exposure parameters have been adopted from film-screen systems. This is commonly the case with computed radiography systems (CR), where the detector system is provided by a different manufacturer from the actual x-ray system. It is not so clear who is responsible for the optimization of this type of system. It is important to ensure the quality of clinical images. These methods always have the problem of subjectivity, but one difficulty, specific to digital images, is that the appearance and presentation of images differs from film-screen images. Radiologists may complain about poor image quality even though the information content of the image is adequate for diagnosis. In addition to observation of the clinical image quality, objective physical optimization studies are needed.

With film-screen systems, image quality was related to the specific dose on the detector. In digital imaging the contrast can be adjusted and the optimal contrast-to-noise ratio (CNR) is the quantity of interest (Bosmans et al. 2005, Tapiovaara 2005, 2006, Doyle et al. 2006, EC 2006). It may provide the possibility to change to spectra with a lower dose without affecting image quality or even providing better image quality. When new optimization is performed for a specific system with a set geometry, the adjustable parameters are the radiation quality and the dose level. Based on simulation studies, higher energy spectra could be more optimal for digital mammography (Dance et al. 2000b, Fahrig and Yaffe 1994a, 1994b, Fahrig et al. 1996). However, these studies need to be experimentally verified.

This thesis concentrates on methods for monitoring patient exposure and calibration issues in medical x-ray imaging, excluding computed tomography. Calibration methods for KAP meters where under inspection and a new monitoring method for mammography was introduced. Differences in radiation spectra between calibration and clinical use were highlighted, especially for KAP meters with a strong energy dependence. Changes in radiation qualities between film-screen and digital imaging were also examined for digital mammography.

2 Patient exposure in x-ray imaging

2.1 Quantities

2.1.1 Measurement quantities

Quantities for patient exposure measurement have been introduced in many publications (ICRU 2005, IAEA 2007). In this chapter, those of most importance with respect to this thesis are introduced. To be able to estimate the effects of radiation, the energy released to a patient is the quantity of interest. The absorbed dose D is the mean radiation energy $d\varepsilon$ transmitted to a mass unit divided by the mass of the unit dm.

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

Kerma (K) is the kinetic energy dE_{tr} released by uncharged particles to charged particles in a mass unit divided by mass of the unit dm.

$$K = \frac{dE_{tr}}{dm} \tag{2}$$

D and K have the same unit, J/kg, and the specific unit in the SI system is the gray (Gy). Typically, in the dosimetry of medical x-ray imaging the medium is air and the quantities used are the dose absorbed in the air (D_{air}) and air kerma (K_{air}). In the energy range of x-ray diagnostics there is an equilibrium of charged particles and $D_{air} \approx K_{air}$ (IAEA 2007). The quantity air kerma has been used in this work as the basis of all directly measured application-specific quantities in accordance with the ICRU (2005) and IAEA (2007).

The most commonly used quantities for patient exposure measurement are the incident air kerma (K_i), entrance surface air kerma (K_e) and kerma-area product (KAP, P_{KA}). The specific term K_i is used for the K_{air} from an incident X-ray beam measured on the central beam axis at the position of the patient or phantom surface, and this is called K_e when the backscattering from the patient or phantom is included. K_e is used to provide a better estimate of the patient skin dose. The kerma-area product of an x-ray beam is the surface integral of air kerma K_{air} over the area A of the entire beam in a plane perpendicular to the beam axis (ICRU 2005, IAEA 2007):

$$KAP = \iint_A K_{air}(x, y)\, dx\, dy \qquad (3)$$

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. However, this approximation is only accurate and reliable in uniform, sharp-edged x-ray fields. Otherwise, non-uniformity of the field may cause inaccuracy in the quantity. K_{air}, K_i and K_e are all quantities for one point. However, the risk to the patient is related to the total exposure and also to size of the radiation field. This is why the *KAP* quantity is more closely related to radiation energy transmitted to the patient and the total dose of the patient (Shrimpton et al. 1984, Le Heron 1992).

2.1.2 Patient doses

The generic term patient exposure has been used for K_{air}, K_i, K_e and *KAP*. These quantities are the ones used in measurements and can be compared to DRLs (EC 1997). None of these is directly proportional to the radiation risk needed for optimization studies and the comparison of different examinations. Therefore, some quantities more closely related to the risk have been evaluated and they can be calculated from these measured quantities (ICRU 2005, ICRP 2007). If the measured quantity is for one point, the radiation field size should be evaluated separately when the total dose or risk to the patient is to be estimated. The effective dose is commonly used for comparisons and for cancer risk estimation. However, the equivalent dose in an organ or tissue would be more accurate for general risk estimation. These quantities are presented in detail elsewhere (ICRP 2007).

In normal mammography (not magnification), the radiation field is of a standard size and it is always larger than the breast. Therefore, it is not of interest to estimate the *KAP* quantity for mammography and calculations are based on air kerma measurements. Because the glandular tissue is the most radiation-sensitive part of a breast, the mean glandular dose (*MGD*) is used for risk estimation in mammography. This is also the quantity recommended for use as a DRL in mammography (EC 1997). The most generally used factors for calculating the *MGD* are those described by Dance et al. (2000a). The *MGD* is calculated from the measured air kerma by using tabulated conversion factors g and correction factors for the spectra (s) and glandularity (c).

$$MGD = K \cdot g \cdot s \cdot c \qquad (4)$$

2.2 Dosemeters and measurements

The basis of all patient dose estimations is the patient exposure quantity to be measured. If tabulated values are used for conversion from a measured to a risk related quantity, the accuracy of the final result can only be adjusted by the accuracy of the measured quantity. Uncertainties can be evaluated on the basis of the Guide to the expression of uncertainty in measurement (ISO 1995). All of the estimated uncertainties in this thesis are reported as expanded total relative uncertainties, obtained by multiplying the combined relative standard uncertainty with the coverage factor, k = 2 (confidence level 95%). In diagnostic x-ray dosimetry, an uncertainty of 7% or lower is recommended for exposure measurements (Wagner et al. 1992, ICRU 2005, IAEA 2007). This sets high requirements for exposure measurement methods and for the calibration of dosemeters. These specific meters are used to detect and measure the amount of radiation. Interaction between the radiation and material is needed to be able to measure the energy released by the radiation.

2.2.1 Dosemeter types

Ionization chambers, thermoluminescent (TLD) and semiconductor dosemeters are generally used for radiation detection in x-ray imaging. The general properties of detectors are presented in the literature (e.g. Knoll 2000), international requirements are given in IEC standards (1997, 2000) and the required performance has been addressed by the American Association of Physicists in Medicine (Wagner et al. 1992). The properties of these meters are discussed in many publications (Mc Keever et al. 1994, Brenier and Lisbona 1998, Aschan 1999, DeWerd and Wagner 1999, Meyer et al. 2001, Zoetelief et al. 2000, Warren-Forward and Duggan 2004, Martin 2007). High quality ionization chambers are very stable, have good repeatability and the response has a small energy dependence, and they are therefore recommended to be used as reference meters in calibration laboratories (IAEA 2007).

Ionization chambers consist of electrodes with a gas cavity between. Gas particles are ionized by the radiation and charged particles moving in the electrical field are collected by the electrodes, allowing the cumulated charge to be measured. The kerma-area product is usually measured, closely according to the definition (equation 3), with a plane-parallel transmission ionization chamber. The signal from a chamber of this type is proportional to the surface integral over the sensitive area of the chamber. It is presupposed in the concept of the kerma-area product that the area of integration in the definition and the sensitive area of the chamber in the measurement are large enough to cover the entire x-ray beam, including the penumbra regions. A KAP chamber consists of polymethyl metharcrylate (PMMA) walls covered with conducting material. The clinical requirement for light transparency limits the possibilities for use as a wall material. Because of the use of materials with a high atomic number, the energy dependence is stronger than for chambers with a graphite coating (Larsson et al. 1996, Bednarek and Rudin 2000).

2.2.3 Estimation of patient exposure

Patient exposure can be estimated in three ways:
1. Phantom measurement
2. Tube output calculation
3. Exposure monitoring

Measurements performed with a standard phantom, simulating an average patient, are good for controlling technical parameters, comparing different systems and optimization. However, these 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.

The tube output (air kerma/tube loading) is separately measured for different radiation qualities and patient exposure is calculated using the display of tube current and exposure time (e.g. STUK, 2004). Actual patient exposure levels can be estimated with the tube output calculation. However, the exposure is not actually measured with any dosemeter and possible malfunctions of the system may remain undetected.

In exposure monitoring, actual measurement of the patient exposure is performed during an experiment with a suitable dosemeter (e.g. KAP, TLD). Exposure can be measured for a specific patient using a TLD, but this method has several limitations. For example, the measurement is labour intensive, cannot be done for all patients and the dosemeter may hide some clinically interesting targets. In general and interventional radiography, KAP meters are often used in the x-ray beam to monitor patient exposure during the examination. The actual exposure level is measured during the examination and feedback on the exposure can be extracted directly. Tube voltages over 50 kV are recommended for KAP meters and therefore they are not suited for mammography with lower tube voltages (under 35 kV).

2.3 Calibration of dosemeters

In order to obtain comparable and reliable results, the calibration of the meter should be traceable to national or international standards. In a primary standard dosimetry laboratory (PSDL), the standard values are measured with an open air ionization chamber, and the dosemeters of a secondary standard dosimetry laboratory (SSDL) are calibrated against this standard. The dosemeter type used in SSDL should be of a reference class, and these requirements are typically only fulfilled by ionization chambers (IAEA 2007).

In the calibration, a calibration coefficient N is calculated. The reference value M_{ref} is measured with a reference dosemeter and is divided by the display of the dosemeter under calibration M_{cal}.

$$N = \frac{M_{ref}}{M_{cal}} \tag{5}$$

In some cases, the dosemeter is part of the x-ray system and cannot be sent to a standard laboratory for calibration. In these cross-calibration cases, field calibration needs to be performed. In this case, the reference dosemeter is used in field measurements and it should have calibration traceable to international measurement standards.

2.4 Radiation qualities

The x-ray spectrum is continuous and includes a large range of energies. This makes it difficult to exactly describe the spectrum and reproduce it with different systems. The term 'radiation quality' is used for the spectrum of radiant energy produced by a given radiation source with respect to its penetration or its suitability for a specific application. The radiation quality of an x-ray beam can be specified, for instance, by the tube voltage and total filtration, together with the anode angle and anode material. The half-value layer (*HVL*) is the most generally used radiation quality specifier when attempting to describe spectra with one parameter. However, real spectra may be very different, even though they have the same *HVL* (Figure 1).

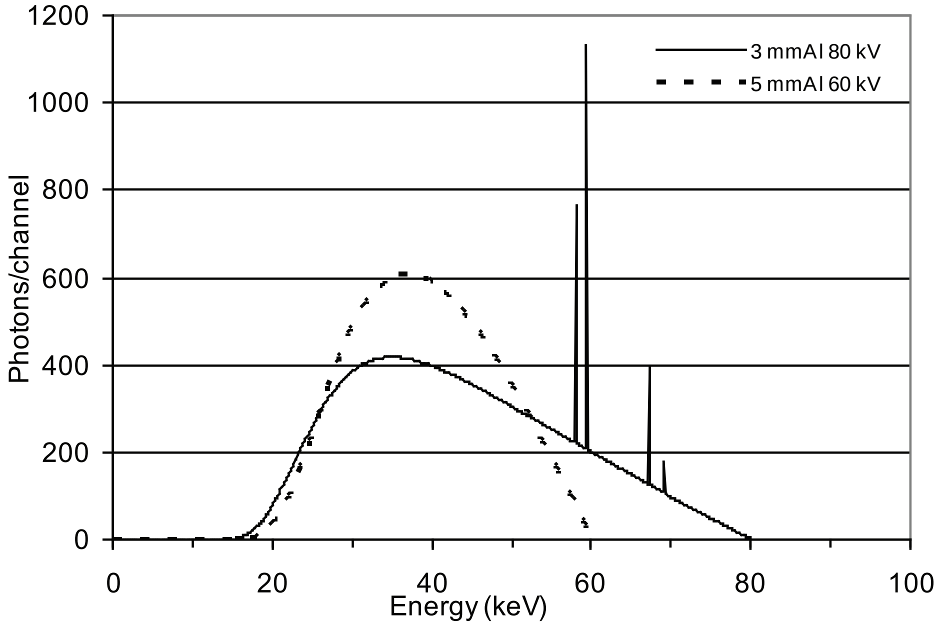

Figure 1. X-ray spectra for two radiation qualities (total filtration and tube voltage) with the same half-value layer of 3 mm Al. The spectra were produced using the computer program Spektripaja (Tapiovaara and Tapiovaara 2008).

2.4.1 Radiation qualities in calibrations

The response of an ideal dosemeter does not have energy dependence and same calibration coefficient can be used for different spectra. An international standard defines the allowed energy dependence for dosemeters (IEC 1997, 2000). The limits of deviation from the reference value (at 100 kV) when the total filtration is 2.5 mm Al and the x-ray tube voltage is between 50 kV and 150 kV are 8% for KAP meters and 5% for others. For other filtrations, no requirements are stated in the standards.

In practice, the energy dependence should be studied in calibrations by using different radiation qualities. Separate radiation quality specific calibration coefficients can be given for different qualities. Another approach is to give one calibration coefficient N for the reference radiation quality Q and a correction factor k_q for the other radiation quality q:

$$k_q = \frac{N(q)}{N(Q)} \tag{6}$$

Standard RQR radiation qualities (IEC 2005, Table 1), intended to represent the x-ray beam incident on the patient in radiographic, fluoroscopic and dental examinations, are generally used for calibration in laboratories (ICRU 2005, IAEA 2007). In mammography, RQR-M qualities are recommended for calibrations (IEC 2005, IAEA 2007). They are based on molybdenum anode-filter combinations and specified tube voltages (25, 28, 30 and 35 kV). Standard radiation qualities do not cover the whole range of radiation qualities used in medical x-ray examinations. The calibration coefficients need to be converted to the actual clinical radiation qualities by interpolation using appropriate specifiers of the energy spectrum. For reference class ionization chambers, the response depends rather smoothly on the radiation energy, and the half-value layer (*HVL*) is often sufficient for specifying the radiation quality for these dosemeter types. However, this may not be the case for dosemeters with a strong energy dependence.

Table 1. RQR standard radiation qualities (IEC 2005) realized at STUK.

Code	Tube voltage (kV)	STUK: Filtration (mm Al)	STUK: HVL (mm Al)	IEC: HVL (mm Al)
RQR 2	40	2.59	1.42	1.42
RQR 3	50	2.59	1.77	1.78
RQR 4	60	2.78	2.16	2.19
RQR 5	70	3.10	2.62	2.58
RQR 6	80	3.02	2.98	3.01
RQR 7	90	3.25	3.48	3.48
RQR 8	100	3.37	3.94	3.97
RQR 9	120	3.82	5.03	5.00
RQR 10	150	4.45	6.60	6.57

2.4.2 Optimal radiation qualities in the clinical situation

Clinical radiation qualities are selected based on many years of experience and optimization. In general, the anode material is tungsten (W) and tube voltages range from 50 kV to 150 kV. Aluminium (Al) is typically used as a filter material to remove the low-energy part of the spectrum, which would simply add to the patient exposure without contributing to the image. Other materials, such as copper (Cu), are sometimes used to further harden the spectrum. In mammography, much lower energies are used because of the thinner imaging target and to achieve better contrast. Tube voltages typically range from 22 kV to 40 kV (IAEA 2007). In film-screen mammography, anodes and filtrations of molybdenum (Mo) have traditionally been the most commonly used, but other choices such as rhodium (Rh) have also been introduced, especially for imaging thick breasts (Gingold et al. 1995, Desponds et al. 1991, Jennings et al. 1981, Dance et al. 2000b). By using K-edge filtrations, higher energies are also filtered and the radiation spectrum can be narrowed to approach the optimal energy spectrum (Bushberg et al. 2002).

Optimization is always a problem with two dimensions. The image quality should be good enough for diagnosis but the patient dose should be kept as low as reasonably achievable (ALARA, ICRP 2007). Good image quality in clinical patient images is the primary task of optimization, and radiologists viewing images have an important role in the optimization process (Tapiovaara 2006). Optimization is difficult with patient images because the target will change in different exposures and extreme values cannot be used. Post-processing of digital images is carried out for patient images and this may induce some problems if it is used for unconventional targets. Therefore, original images (for processing) should be used when phantom images are examined and post-processing should be optimized separately. Methods for optimizing post-processing are presented, for example, by Carton et al. (2003) and Zanca et al. (2006). Technical measurement can be used as a primary method for the optimization of image acquisition.

The visibility of the object in the image is dependent on the contrast, noise and sharpness. The radiation quality determines the intrinsic x-ray contrast generated by the tissues and the x-ray contrast decreases for higher beam energies. The quantum noise primarily depends on the number of absorbed quanta, and is then also affected by the beam quality. The beam quality does not have a significant effect on the sharpness of the digital detector. With film-screen systems, the film-specific air kerma level is needed for good image quality. Therefore, optimization is mainly based on the contrast determined by the radiation quality. In digital systems, the optimal air kerma level can be chosen and the contrast can be adjusted at the expense of affecting the noise. Since the effects of contrast, image sharpness and noise are interrelated and dependent on some characteristics specific to the imaging system, new optimization is needed for new detectors. Because the resolution is not expected to change significantly with the exposure parameters, measurements of the contrast-to-noise ratio (*CNR)*[*)] are considered a valuable tool in image quality optimization for a particular system (e.g. Bosmans et al. 2005, Tapiovaara 2005, 2006, Doyle et al. 2006, EC 2006). In *CNR* the difference between the signal from the target

[*)] In study V the term signal difference-to-noise ratio (SDNR) was used for this same quantity.

(S) and background (B) is divided by the root-mean-squared noise from the signal σ_S and background σ_B.

$$CNR = \frac{S - B}{\sqrt{\frac{(\sigma_s^2 + \sigma_B^2)}{2}}} \tag{7}$$

To be able to optimise not only the technical image quality but the actual clinical image quality, the choice of target and background for *CNR* measurement is important, and they should simulate the clinical targets and backgrounds (Tapiovaara 2006).

Radiation qualities other than conventional ones used with film-screen systems may be optimal for new digital systems. Especially in mammography, lower energies have been used to achieve sufficient contrast. With digital systems, the contrast is adjustable and radiation qualities with higher energies could be used, at least with thicker breasts (Fahrig and Yaffe 1994a and b, Fahrig et al. 1996, Venkatakrishnan et al. 1999, Dance et al. 2000b, Berns et al. 2003, Obenauer et al. 2003, Young et al. 2006).

3 Methods

3.1 Monitoring patient exposure

3.1.1 Kerma-area product meter

KAP meters are generally used to monitor the beam of an x-ray system and patient exposure. To achieve adequate accuracy in *KAP* measurements, appropriate calibration of the KAP meter is needed. In study I, a new calibration method for field KAP meters, a tandem method, was introduced and examined. In this method, the field KAP chamber is positioned similarly to measurements with patients and the reference KAP meter is simultaneously used in the beam. For this purpose, a Diamentor M4 (PTW, Germany) KAP meter was calibrated in the SSDL laboratory for the incident beam and was used as a reference meter on a clinical site. The appropriate calibration geometry (measurement distance and field size) for the tandem method was studied.

Other calibration methods, namely the beam area and laboratory method, were also used for calibration and the results and uncertainties were compared with the tandem method. In the beam area method, the *KAP* quantity was approximated by the product of the measured air kerma and the radiation field size. In the laboratory method, the field KAP meter was calibrated in the laboratory for transmitted radiation. The effects of unit-specific radiation were assessed to demonstrate the uncertainty of the uncorrected laboratory calibration. The field KAP chamber was used in its conventional position d_0 , and also at a longer distance, $d = d_0 + 30$ cm. The unit-specific correction factors $k(d,d_0)$ were calculated as the quotient of the KAP meter readings $M(d)$ and $M(d_0)$:

$$k(d,d_0) = M(d) / M(d_0) \tag{8}$$

Multiplication by this correction factor converts the laboratory-provided calibration coefficient N and the *KAP* value to distance d, while the KAP meter is used at d_0.

3.1.2 Digital detector

KAP meters cannot be used in mammography and other methods are therefore needed for exposure monitoring. In study IV, the use of pixel values from the detector elements in the unattenuated primary beam area to monitor the incident air kerma (PV method) was investigated for two direct digital mammography systems. The detector of system 1, Nuance Excel (Planmed Oy, Helsinki, Finland), is based on amorphous selenium direct conversion technology and system 2, Senographe Essential (GE Medical systems, Buc, France), on indirect conversion with a CsI scintillator and amorphous silicon technology. The repeatability and response of the two direct digital detector types were assessed with a large exposure range and different radiation qualities. Using these calibration results, air kerma was measured from clinical images and compared to the tube output calculation.

3.2 Radiation qualities

3.2.1 From calibrations to clinical use

The difference between standard and clinical radiation qualities was analyzed. The effect of differences was examined more carefully for KAP meters, which are known to have a strong energy dependence. Calibration coefficients of KAP meters were determined in studies II and III using the RQR standard radiation qualities (Table 1) and several other qualities that are typically used in medical x-ray units. For these clinical radiation qualities, the tube voltages ranged from 40 kV to 150 kV and aluminium filters of different thickness and together with copper were used. In study II, calibration coefficients were examined for 11 traditional KAP meters manufactured for clinical purposes and in study III, for a new large non-transparent kerma-area product meter (patient dose calibrator, PDC, Radcal).

The results were examined with respect to radiation energy using different specifiers for the energy distribution of the x-ray beam. The accuracy of *KAP* measurements at different radiation qualities was investigated, especially with respect to the interpolations between the radiation qualities used in calibration procedures when determining the calibration coefficients needed in clinical practice.

3.2.2 From film-screen to digital mammography

In routine practice, the direct digital mammography system Novation DR (Siemens, Erlangen, Germany), examined in study V, uses a tungsten (W) anode in combination with a 50 µm thick rhodium (Rh) filter, and for thin breasts a molybdenum (Mo) anode together with a 25 µm Rh filter, instead of the conventional combination of an Mo anode with an Mo filter (30 µm). Study V investigated whether occasionally poor image quality was related to the use of these anode/filter combinations or some other factor. An optimization study of exposure parameters (radiation quality and dose level) was performed for this system. For this purpose, the SDNR (another term for CNR) was used to estimate image quality and mean glandular doses (MGD) to estimate the risk for a patient. An optimization study was performed with different breast thicknesses (from 2 cm to 7 cm), dose levels and radiation qualities. All available anode/filter combinations (Mo/Mo, Mo/Rh and W/Rh) and a tube voltage range from 23 kV to 35 kV were used.

4 Results

4.1 Monitoring patient exposure

4.1.1 Kerma-area product meter

Based on study I, the tandem method provides a feasible and practical way to calibrate field KAP meters of any type in their clinical position. Accurate measurements of the irradiation geometry are not required, but comprehensive calibration for the reference KAP meter is needed. The results for the field KAP meter calibrated with three methods are presented in Figure 2. The larger difference between the tandem method and laboratory method was circa 5%. After unit-specific correction of the laboratory method, the difference was reduced to 1%.

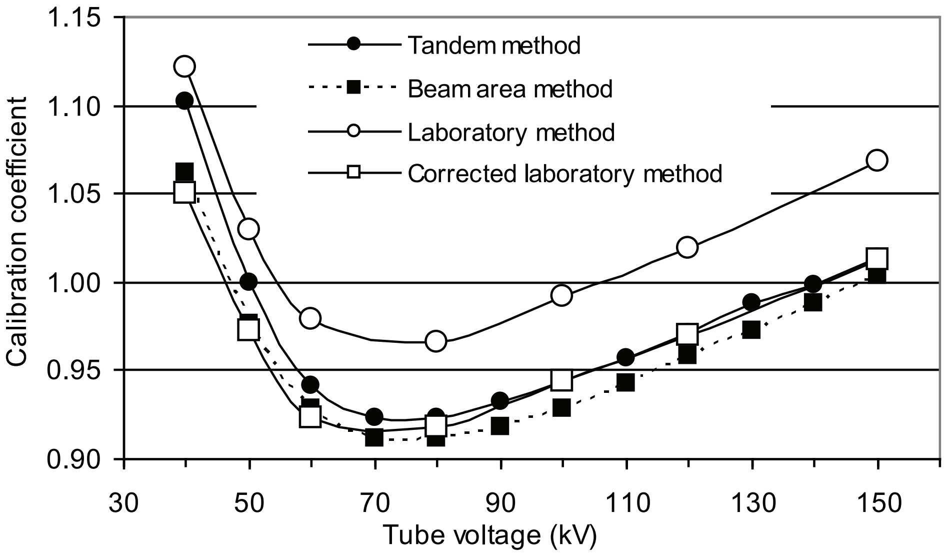

Figure 2. Calibration coefficients for three different calibration methods: the tandem, beam area and laboratory method (see study I for a full description of the methods). The total filtration was 4.8 mm Al in the tandem and beam area methods and 5 mm in the laboratory method. In measurements of the unit-specific correction for the laboratory method the total filtration was 4.8 mm Al. The field size was 6 cm x 6 cm at the reference measurement distance. The total uncertainties of the calibration coefficients for the tandem method are 5.4% for ≥ 60 kV and 6.7% for lower tube voltages, for the beam area method 7.5% and for the corrected laboratory method 6.4 – 7.8% (confidence level 95%). (Study I)

In the tandem calibration method, the estimated total relative uncertainty of calibration coefficients for the field KAP meter was 5.4 – 6.7%, depending on the radiation quality. This estimation is only for the calibration coefficient and the part of the uncertainty from careful measurement and calculation of the *KAP* value for a patient is typically 3–4% under good conditions. It means that the uncertainty of the calibration coefficient should not exceed 6% to achieve the total relative uncertainty of 7%. With these uncertainties, the recommended accuracy in *KAP* measurement can only be achieved in a limited range of radiation qualities.

4.1.2 Digital detector

According to study IV, the air kerma estimation based on the pixel values from direct digital detectors can be used for patient exposure monitoring in digital mammography. The main advantage of the method is that it is based on real measurement from an actual exposure, and changes in exposure that would not be captured by tube output calculation can therefore be detected. In the repeat measurements of pixel values the drop in values for the very first image observed by Pöyry et al. (2006c) was found not to be related to a drop in the air kerma level. However, other changes and the trend in pixel values during the measurement session were related to changes in air kerma.

For the studied system, the difference in air kerma can be over 40% for different radiation qualities but with the same pixel value. This highlights the issue that an exposure or similar index cannot be used for accurate exposure estimation without separate conversion factors for different radiation qualities. In study IV, the conversion factors were measured and used for clinical images. A comparison of the pixel value method and the tube output calculation with clinical images is presented in Figure 3. The differences between the two methods were typically under 2%. The estimated total uncertainty of the method (6.9%) is comparable to the accuracy of the tube output calculation, and the recommended accuracy can be achieved with the pixel value method.

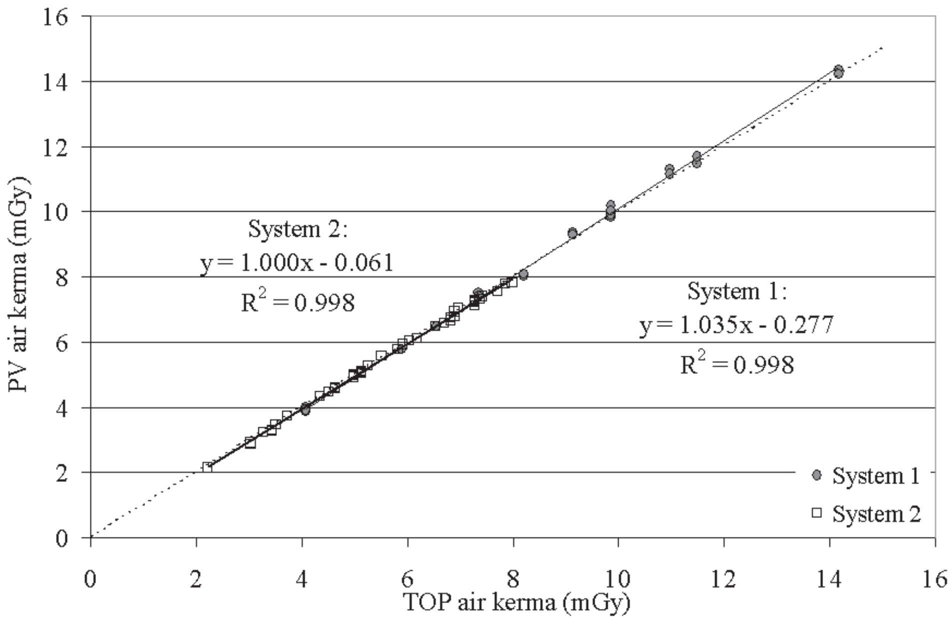

Figure 3. Comparison of air kerma at 0.5 m distance from the focal point in patient examinations for systems 1 and 2. Air kerma was calculated based on pixel values (PV) and tube output measurement (TOP). The equation for the linear trend line (continuous) fitted to the points is presented in the figure (thinner line for system 1 and thicker for system 2). The broken line indicates unity (y = x). The total uncertainty of air kerma is 6.9% (confidence level 95%) for both methods. (Study IV)

4.2 Radiation qualities

4.2.1 From calibrations to clinical use

Standard radiation qualities (e.g. RQR, Table 1) differ from the ones used in patient imaging and they do not cover the total *HVL* range of clinical use. For example, if a filter with a higher atomic number (e.g. copper) is used together with higher tube voltages (>100 kV), the *HVL* is higher than with largest RQR quality (IEC 2005), and extrapolation is needed. This situation is also the same for mammography, in which the highest *HVL* of standard radiation qualities is 0.36 mmAl (RQR-M 4, 35 kV) and for radiation qualities used in clinical imaging, *HVL* may be >0.5 mm Al. Extrapolation of calibration coefficients cannot be recommended for any dosemeter. Interpolation of calibration coefficients in the range of standard radiation qualities can be performed if the response of a dosemeter has a small energy dependence. For example, the standard radiation qualities recommended for mammography are based on an Mo/Mo anode/filter combination, although other combinations such as Mo/Rh, Rh/Rh and W/Rh are also used in clinical imaging. However, high quality ionization chambers recommended for mammography have a small energy dependence (DeWerd et al. 2002, Witzani et al. 2004), and *HVL* can therefore be used to specify the radiation spectra and for interpolation of the calibration coefficient. This is not the case for a dosemeter with a strong energy dependence.

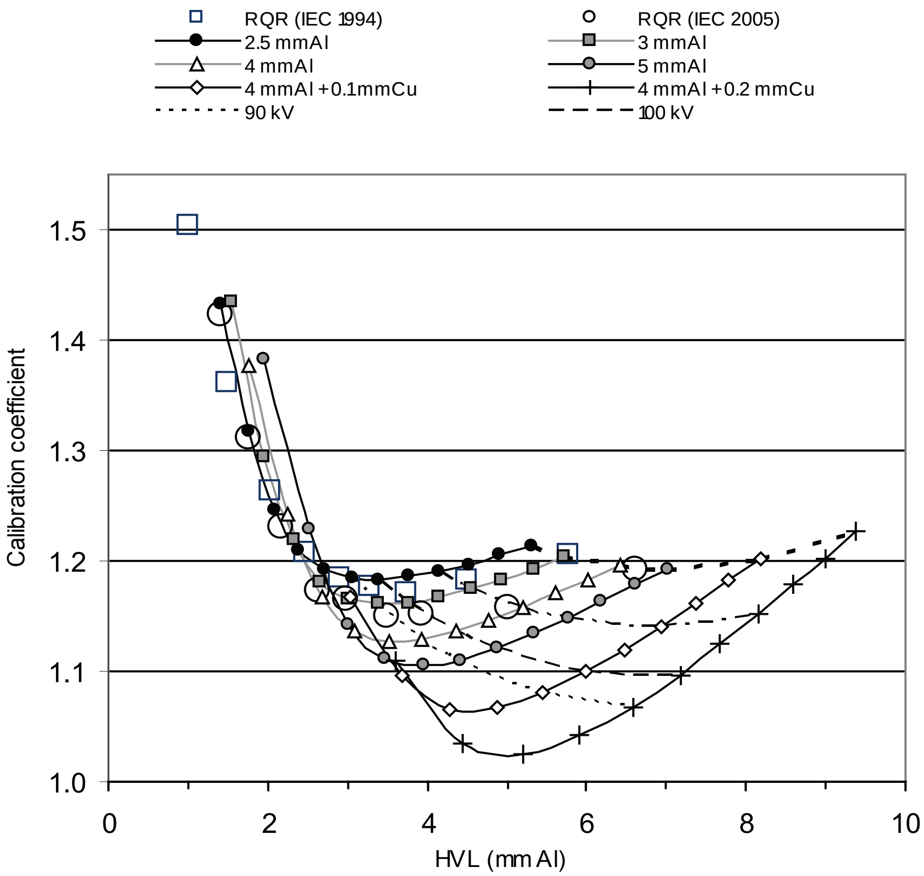

Figure 4. Calibration coefficients of the Diamentor M4 KAP meter for an x-ray beam incident on the chamber, for different total filtrations and RQR standard radiation qualities (IEC 1994 and 2005), presented as a function of the half-value layer (*HVL*). Calibration coefficients for the tube voltages of 90, 100, 120 and 150 kV are connected by dotted lines. (Study II)

The energy dependence was significant for all examined clinical KAP meters and the shape of calibration curve varied between different KAP meter types. Calibration coefficients for one typical KAP meter are presented as a function of the *HVL* in Figure 4. The difference between the highest and lowest calibration coefficients is 40%.

To achieve the 7% uncertainty level for clinical *KAP* measurements, the field KAP meter should be calibrated for an appropriate number of clinical radiation qualities. To obtain the correct magnitude of estimation for exposure in the clinical situation, the field KAP meter could be adjusted with a selected average radiation quality from the range of radiation qualities to be used in practice. Radiation quality specific coefficients can be used for the calculation when more accurate results are needed.

If a KAP meter is calibrated in the laboratory with standard radiation qualities, the adequate specification for the spectrum is needed to be able to interpolate the calibration coefficients for clinical radiation qualities. For accurate measurements, it is not sufficient to make the interpolation based on a single parameter, such as the x-ray tube voltage, total filtration or *HVL*: at least two parameters are needed to specify the x-ray spectrum. If possible, the radiation qualities that are used in clinical measurements should be simulated in the calibration. If this is not possible, extensive calibration covering the clinical range is necessary. The easiest approach would be to perform the calibration with fixed filtration and a certain tube voltage range, and to then determine the correct calibration coefficient by interpolation between these data by using two specifiers. Calibration of KAP meters by using the IEC RQR radiation qualities results in unacceptable errors if the actual filtration of the clinical x-ray beam markedly differs from that used in realizing the RQR spectrum.

The energy dependence of a new PDC kerma-area product meter was also studied and calibration coefficients are presented in Figure 5. This type of KAP meter has a lower energy dependence than typical transparent KAP meters, and *HVL* can be used as a radiation quality specifier with an uncertainty lower than 2%. The uncertainty of calibration coefficients of a field KAP meter calibrated with the tandem method can be reduced to 4.9% by using this meter type as a reference meter.

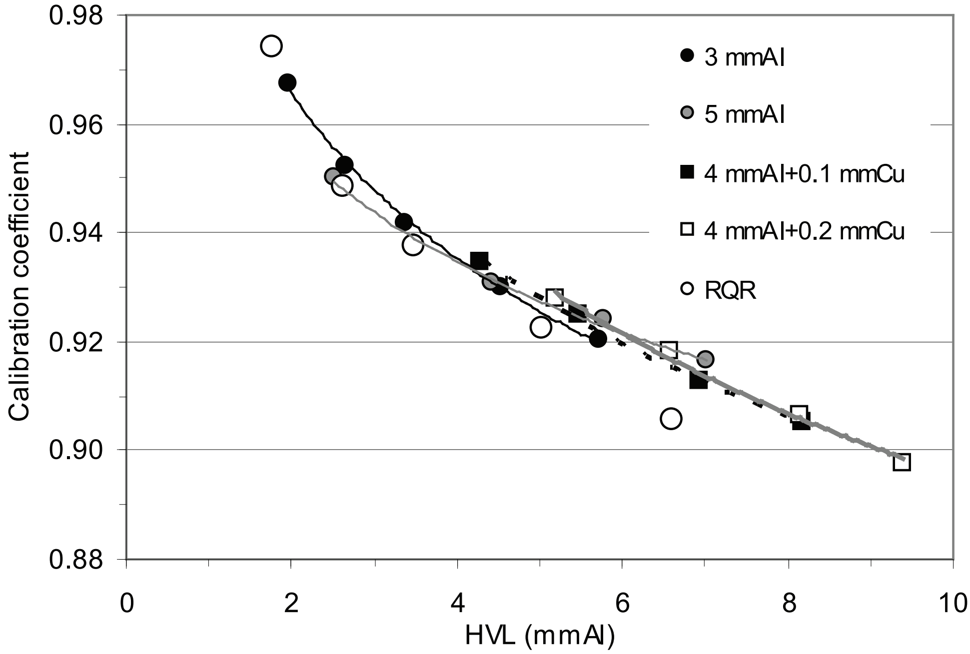

Figure 5. Calibration coefficients of the PDC-1 meter (Radcal) for an x-ray beam incident on the chamber, for different total filtrations and RQR standard radiation qualities (IEC 2005), presented as a function of the half-value layer (*HVL*). The logarithmic trend line is fitted to the points with fixed filtrations. (Study III)

4.2.2 From film-screen to digital mammography

Many digital mammography systems still use a conventional Mo/Mo anode/filter combination, although based on simulation studies some other combination could be more optimal for digital systems. However, in the studied system, other combinations were used. An optimization study was performed and in Figure 6, the calculated SDNR is plotted as a function of the MGD for three different PMMA thicknesses (2 cm, 5 cm and 7 cm) and three anode/filter combinations. The SDNR of the W/Rh anode/filter combination is always highest for a given dose, and the same trend appeared for all thicknesses and tube voltages. By using a tungsten anode in combination with a rhodium filter, the same SDNR can be achieved with a significantly lower MGD than by using a molybdenum anode in combination with an Mo or Rh filter. This difference is largest for the thickest breasts, but it applies for all breast thicknesses, and the use of the W/Rh combination can therefore be recommended for all breast thicknesses.

For some thicknesses, the dose levels provided by the clinically used AEC mode achieved SDNR values that were probably too low for good image quality.

However, the dose level of the system was very low for the W/Rh combination compared to most film-screen systems. This low dose setting was attributed as the main reason for the occasionally poor image quality in clinical mammograms. As a result of our study, the AEC setting was reset for a higher dose level, which was still lower than generally used with film-screen systems. Based on clinical estimation, the image quality improved to an appropriate level.

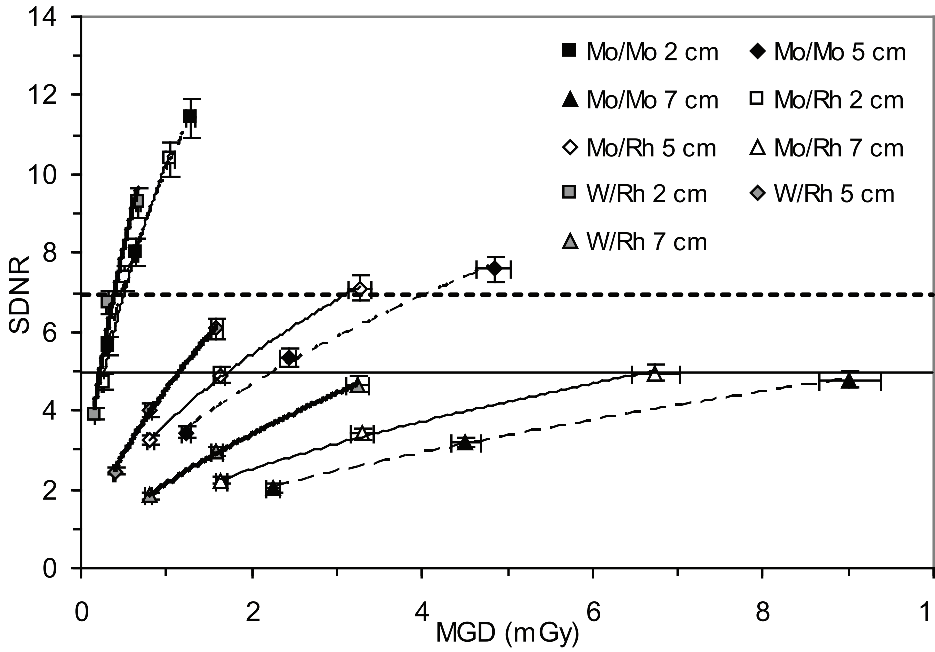

Figure 6. The signal difference to noise ratio (SDNR) as a function of mean glandular dose (MGD) for a peak tube voltage of 27 kV and for three PMMA thicknesses and anode/filter materials. The three points in each curve correspond to three different dose levels (the middle point chosen to be near to the value that automatic exposure control would select). Uncertainties of 4.3% for the SDNR and 4.1% for the MGD (95% confidence level) are shown with error bars. SDNR levels of 5 (continuous line) and 7 (dashed line) are plotted. (Study V)

5 Discussion

5.1 Monitoring patient exposure

Feedback on patient exposure is important for a user to be able to optimize the use of radiation. The value can be based on calculations, but direct measurement has some advantages compared to indirect exposure estimation. Changes in air kerma that would not be noted from exposure parameters, such as the effect of a short exposure or incorrect filtration, can be revealed. Especially with digital systems, some malfunctions of the system can only be detected by measurement, because a high air kerma will not overexpose the film. A monitoring device can also be used to check the output stability of the x-ray system by repeating the exposure with the same settings (radiation quality, tube loading and beam area). Comparison of results from direct measurement and the tube output calculation will provide additional information on the reliability of both dosimetric approaches.

KAP meters are easy to use and can provide useful values for patient exposure estimation. However, it is important to properly calibrate a field KAP meter at the clinical site. If the field KAP meter is calibrated in the laboratory, clinical correction measurements should be performed. The tandem calibration method, introduced in study I, is straightforward to perform in the clinical environment, because accurate adjustment of the reference meter or field size measurement is not required. However, a reference KAP meter with extensive calibration is needed. This is why this method is most useful for situations where the same reference meter can be used for many calibrations and for the testing of field KAP meters. The tandem method was reported together with other methods in a Finnish publication (Toroi et al. 2008) that provided standardized methods for the calibration of KAP meter for users of x-ray systems in Finland. Our preliminary studies with KAP meters (Pöyry et al. 2005, 2006 a, b) were also recognized by IAEA in the International Code of Practice for diagnostic radiology (2007) and the tandem method was included in cross-calibration methods for clinical KAP meters. The implementation of this guideline was studied by a group of experts gathered by the IAEA and a technical document about the work of this group is expected to be published in 2009. Our work with KAP meters (studies I, II and III) also has an important role in this publication.

Independently of the calibration method, the energy dependence of the response of commercial clinical KAP meters has such an influence that with one electrical adjustment of meter, the recommended accuracy (uncertainty <7%) is difficult to achieve. This problem has been highlighted in paediatric examination, where low tube voltages and thick filtrations are used (Vano et al. 2008c). Calibration and electrical adjustment of a field KAP meter should be properly performed with at least one radiation quality, and in this way the meter can be used to estimate the magnitude of exposure in the clinical situation. More calibration coefficients can be used when accurate exposure estimation is needed, for example, if exposure levels for DRLs are collected or an optimization study is performed.

KAP meters cannot be used for exposure monitoring in mammography, and a new method for this purpose was proposed in study V. The use of pixel values for exposure monitoring is an appropriate method for estimating air kerma in patient examinations. However, the response of this dosemeter also has energy dependence, and radiation quality correction factors are needed when accurate measurements are to be performed. In the future, pixel values could also be used for measuring the patient dose and risk-related quantities. The usefulness of the pixel value method could also be studied for other modalities. To be able to use the pixel value for exposure estimation or for other physical measurements, original data without image-specific processing are needed. With help from the manufacturer, the original pixel values from a selected reference ROI could be added in the Dicom header.

It is not relevant to compare the results from individual examinations, but instead to compare the general levels. In digital imaging, not only the image data but also exposure parameters are typically stored in a digital format. In direct digital systems, exposure information and sometimes also *KAP* measurement results are stored in the Dicom header. This property of new systems provides a possibility to automatically collect patient data for a large patient volume (Vano et al. 2002, Vano and Fernandez 2007). Automation would free users from collecting patient examination data.

5.2 Radiation qualities

The difference between standard and clinical radiation qualities causes a problem in situations where extrapolation is needed or the response of a dosemeter has a strong energy dependence. The response of clinical KAP meters has strong a energy dependence and the *HVL* cannot be used alone to specify radiation spectra for interpolations. The radiation quality dependence of KAP meters, seen in study II, is the main drawback of the tandem method, but the new PDC type KAP meter examined in study III could be a solution to this problem. By using this meter type as a reference meter in the tandem calibration method, the accuracy of the calibration coefficient can be improved and an uncertainty of ≤7% can be achieved in *KAP* measurements.

To our knowledge, study III was the first scientific publication concerning the PDC meter type, and more studies should be performed to specify other characteristics of this meter type. For example, the field size dependence of the response should be assessed. However, this PDC meter type cannot be used as a field instrument for patient exposure monitoring, and it will not resolve the problem of the energy dependence of clinical KAP meters. Manufacturers will have an important role in the future to provide meters with smaller energy dependences. Another possibility with digital systems is to include some automated calculation program to which calibration coefficients for different radiation qualities could be entered to provide corrected results.

Changing over to digital imaging also makes it important to provide new optimization of radiation qualities and exposure levels for the new detectors. In our study V, the use of the W/Rh anode/filter combination was investigated for one direct digital mammography system. It was concluded that W/Rh would actually provide the best results for all breast thicknesses, not only for thicker breasts, as suggested by a simulation study (Dance et al. 2000b). The selection of the tube voltage did not have such a large influence. However, in this case, dose levels were set to be optimal for the old Mo/Mo combination and the level was too low for this system. Adjustment of the system improved the image quality to an appropriate level. Since this study, similar results have also been reported by other researchers (Muhogora 2008, Williams 2008).

6 Conclusions

Accurate and reliable estimation of patient exposure can be achieved by using a properly calibrated exposure monitoring dosemeter. KAP meters have been used for this purpose in general x-ray imaging, and for mammography a new possibility is the use of pixel values from digital detectors. With these monitoring dosemeters, internationally recommended accuracy levels can only be achieved in exposure measurements if radiation quality correction factors are used in the measurements. If clinical radiation qualities differ from those used in the calibration, the *HVL* cannot alone be used for the interpolation. When switching from film-screen to digital systems, clinically used radiation qualities and exposure levels should be re-optimized for the new detectors. At least for some mammography systems, it is possible to reduce the exposure level with an appropriate selection of radiation qualities.

In the tandem method, a field KAP meter is calibrated using a reference KAP meter, and some disadvantages of traditional methods can be avoided. The tandem method is easy to perform in clinical x-ray units, and is not sensitive to minor changes in calibration geometry. This method was also adopted in international recommendations. The main drawback of the method is the uncertainty arising from the dependence of the response of the reference KAP meter on the x-ray energy spectrum. If the clinical KAP meter type is used as a reference meter, the achieved accuracy of the calibration coefficient is only slightly better than with traditional beam area method or laboratory method.

The energy dependence of the response of clinical KAP meters has the effect that, independently of the calibration method, radiation quality specific correction factors are generally needed in clinical measurements to achieve the recommended accuracy level. Another issue is that if different radiation qualities are used in calibration and in measurements, care should be taken in the interpolation of calibration coefficients. The *HVL* cannot be used alone to specify the radiation spectra, and at least two specifying parameters from among the tube voltage, filtration or *HVL*, should be used. For current standard radiation qualities, none of these parameters is fixed and interpolation is difficult. In addition, they do not cover the range of clinical need and the user may have to extrapolate the calibration coefficient. This is emphasized with conventional KAP meters that have a strong energy dependence. The novel PDC KAP meter type meter has a much smaller energy dependence. The accuracy of the tandem method is improved if this meter type is used as a reference meter, and the recommended accuracy can be achieved in *KAP* measurements.

Pixel values from a digital detector provide a real exposure measurement result for optimization studies and exposure monitoring. The information is in digital format and can easily be used for the automatic collection of data from a large group of images. Original images (for processing) are needed to be able to use pixel values for optimization or exposure monitoring. This raw data is sometimes not easily available to the user and help from the manufacturer is needed. An actual exposure measurement using pixel values will reveal changes in the x-ray tube output that would not be detected from exposure parameters. An uncertainty level of lower than 7% can be achieved if radiation quality correction factors are used. Pixel values can also be used to measure the image quality in optimization studies. For the direct digital system, an unconventional radiation quality with the W/Rh anode/filter combination gave the best results for all breast thicknesses, and the dose level could be reduced below the level generally used in film-screen imaging. However, it is important to ensure that the dose level is high enough for diagnosis.

7 Aknowledgements

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References

Ariga E, Shigeki I, Shizuhiko D, Takuya S, Kunihide N. 2007 Development of dosimetry using detectors of diagnostic digital radiography systems. Med. Phys. 2007; 34: 166–174.

Aschan C. Applicability of thermoluminescent dosimeters in X-ray organ dose determination and in the dosimetry of systemic and boron neutron capture radiotherapy. Report series in physics, HU-P-D77. Helsinki: University of Helsinki; 1999. http://urn.fi/URN:ISBN:951-45-8686-7

Bednarek DR, Rudin S. Comparison of two dose-area-product ionization chambers with different conductive surface coating for over-table and under-table tube configurations. Health Phys. 2000; 78: 316–321.

Berns EA, Hendrick RE, Cutter GR. Optimization of technique factors for silicon diode array full-field digital mammography system and comparison to screen-film mammography with matched average glandular dose. Med. Phys. 2003; 30: 334–340.

Bosmans H, Carton A-K, Rogge F, Zanca F, Jacobs J, Van Ongeval C, Nijs K, Van Steen A Marchal G. Image quality measurements and metrics in full field digital mammography: an overview. Rad. Prot. Dosim. 2005; 117: 120–130.

Brenier JP, Lisbona A. Air kerma calibration in mammography of thermoluminescence and semiconductor dosemeters against an ionization chamber. Rad. Prot. Dosim. 1998; 80: 239–241.

Bushberg JT, Seibert JA, Leidholdt EM, Boone JM. The Essential Physics of Medical Imaging. 2nd ed. Philadelphia: LWW; 2002.

Carton AK, Bosmans H, Van Ongeval C, Souverijns G, Rogge F, Van Steen A, Marchal G. Development and validation of a simulation procedure to study the visibility of microcalcifications in digital mammograms. Med. Phys. 2003; 30(8): 2234–2240.

Cusma JT, Bell MR, Wondrow MA, Taubel JP, Holmes DR. Real-time measurement of radiation exposure to patients during diagnostic coronary angiography and percutaneous interventional procedures. J. Am. Coll. Cardiol. 1999; 33: 427–435.

Dance DR, Skinner CL, Young KC, Beckett JR, Korte CJ. Additional factors for estimation of mean glandular breast dose using the UK mammography dosimetry protocol. Phys. Med. Biol. 2000a; 45: 3225–3240.

Dance DR, Thilander Klang A, Sandborg M, Skinner CL, Castellano S, Alm Carlsson G. Influence of anode/filter material and tube potential on contrast, signal-to-noise ratio and average absorbed dose in mammography: a Monte Carlo study. Br. J. Radiol. 2000b; 73: 1056–1067.

Desponds L, Depeursinge C, Grecescu M, Hessler C, Samiri A, Valley JF. Influence of anode and filter material on image quality and glandular dose for screen-film mammography. Phys. Med. Biol. 1991; 36: 1165–1182.

DeWerd LA, Wagner LK. Characteristics of radiation detectors for diagnostic radiology. Appl. Radiat. Isot. 1999; 50: 125–136.

DeWerd LA, Micka JA, Laird RW, Pearson DW, O'Brien M, Lamperti P. The effect of spectra on calibration and measurements with mammographic ionization chambers. Med. Phys. 2002; 29: 2649–2654.

Doyle P, Martin CJ, Gentle D. Application of contrast-to-noise ration in optimizing beam quality for digital chest radiography: comparison of experimental measurements and theoretical simulations. Phys. Med. Biol. 2006; 51: 2953–2970.

European Commission (EC). Council directive 97/43/Euratom on health protection of individuals against the dangers of ionizing radiation. Official Journal of the European Communities, No. L 180/22. Luxembourg: CEC; 1997.

European Commission (EC). (2006) European guidelines for quality assurance in breast cancer screening and diagnosis. 4th edition. Luxembourg: Office for Official Publications of the European Communities; 2006.

Fahrig R, Yaffe MJ. A model for optimization of spectral shape in digital mammography. Med. Phys. 1994a; 21:1463–1471.

Fahrig R, Yaffe MJ. Optimization of spectral shape in digital mammography: Dependence on anode material, breast thickness, and lesion type. Med. Phys. 1994b; 21: 1473–1481.

Fahrig R, Rowlands JA, Yaffe MJ. X-ray imaging with amorphous selenium: Optimal spectra for digital mammography. Med. Phys. 1996; 23: 557–567.

Floyd CE Jr, Chotas HG, Dobbins JT 3rd, Ravin CE. Quantitative radiographic imaging using a photostimulable phosphor system. Med. Phys. 1990; 17(39): 454–459.

Gingold EL, Xizeng W, Barnes GT. Contrast and Dose with Mo-Mo, Mo-Rh and Rh-Rh Target-Filter Combinations in Mammography. Radiology 1995; 195: 639–644.

Hetland PO. Friberg EG, Øvrebøø KM, Bjerke HH. Calibration of reference KAP-meters at SSDL and cross calibration of clinical KAP-meters. Acta Oncologica 2009; 48(2): 289–294.

International Atomic Energy Agency (IAEA). Dosimetry in diagnostic radiology: An international code of practice. Technical report series no. 457. Vienna: IAEA; 2007.

International Electrotechnical Commission (IEC) Medical diagnostic X-ray equipment – radiation conditions for use in the determination of characteristics. IEC-1267. Geneva: IEC; 1994.

International Electrotechnical Commission (IEC). Medical Electrical Equipment – Dosimeters with Ionization Chambers and/or Semiconductor Detectors as Used in X-Ray Diagnostic Imaging. IEC-61674. Geneva: IEC; 1997.

International Electrotechnical Commission (IEC). Medical Electrical Equipment – Dose Area Product Meters. IEC 60580. 2nd ed. Geneva: IEC; 2000.

International Electrotechnical Commission (IEC). Medical diagnostic X-ray equipment – Radiation Conditions for use in the determination of characteristics. IEC 61267. Geneva: IEC; 2005.

International Electrotechnical Commission (IEC). Medical electrical equipment – Characteristics of digital X-ray imaging devices – Part 1–2: Determination of the detective quantum efficiency – Detectors used in mammography. IEC 62220-1-2. 1st ed. Geneva: IEC; 2007.

International Electrotechnical Commission (IEC) Medical electrical equipment – Exposure index of digital X-ray imaging systems – Part 1: Definitions and requirements for general radiology. IEC 62494-1. 1st ed. Geneva: IEC; 2008.

International commission on radiological protection (ICRP). The Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 2007; 37(2–4): 1–332.

International Commission on Radiation Units and Measurements (ICRU). Patient dosimetry for x-rays used in medical imaging. ICRU Report 74. J. ICRU 2005; 5(2): 1–113.

International Organization for Standardization (ISO). Guide to the expression of uncertainty in measurement. Geneva: ISO; 1995.

Jankowski J, Domienik J, Papierz S, Padovani R, Vano E, Faulkner K. An international calibration of kerma–area product meters for patient dose optimisation study. Rad. Prot. Dosim. 2008; 129 (1–3): 328–332.

Jennings RJ, Eastgate RJ, Siedband MP, Ergun DL. Optimal x-ray spectra for screen-film mammography. Med. Phys. 1981; 8: 629–639.

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

Kauppinen E. Annoksen määrittäminen mammografiassa digitaalisesta kuvainformaatiosta. (Determining patient dose in mammography from digital image information). Licentiate thesis. Jyväskylä: University of Jyväskylä; 2008. http://urn.fi/URN:ISBN:978-951-39-3295-4. (In Finnish)

Kiljunen T. Patient doses in CT, dental cone beam CT and projection radiography in Finland, with emphasis on paediatric patients. STUK-A232. Helsinki: Radiation and Nuclear Safety Authority; 2008. http://urn.fi/URN:ISBN:978-952-478-408-5

Knoll GF. Radiation detection and measurement. 3rd ed. New York: John Wiley and Sons; Inc.; 2000.

Lampinen J. Calculating patient specific doses in X-ray diagnostics and from radiopharmaceuticals. Report series in physics, HU-P-D82. Helsinki: University of Helsinki; 2000. http://urn.fi/URN:ISBN:951-45-9152-6

Larsson JP, Persliden J, Sandborg M, Alm Carlsson G. Transmission ionization chambers for measurements of air collision kerma integrated over beam area. Factors limiting the accuracy of calibration. Phys. Med. Biol. 1996; 41: 2381–2398.

Larsson JP, Persliden J, Sandborg M, Alm Carlsson G. Ionization chambers for measuring air kerma integrated over beam area. Deviations in calibration values using simplified methods. Phys. Med. Biol. 1998; 43: 599–607.

Larsson JP, Malusek A, Persliden J, Alm Carlsson G. Energy dependence in KAP-meter calibration coefficients: Dependence on calibration method, type of KAP-meter, and added filter close to the KAP-meter In: Thesis of Larsson JP. Calibration of ionization chambers for measuring air kerma integrated over beam area in diagnostic radiology. Factors influencing the uncertainty in calibration coefficients. Linköping University Medical Dissertations No. 970. Linköping: LiU-Tryck; 2006.

Le Heron JC. Estimation of effective dose to the patient during medical x-ray examination from measurements of the dose-area product. Phys. Med. Biol. 1992; 37: 2117–2126.

Lin PJ. The operation logic of automatic dose control of fluoroscopy system in conjunction with spectral shaping filters. Med. Phys. 2007; 34: 3169–3172.

Malusek A, Larsson J P, Alm Carlsson G. Monte Carlo study of the dependence of the KAP-meter calibration coefficient on beam aperture, x-ray tube voltage and reference plane. Phys. Med. Biol. 2007; 52: 1157–70.

Martin CJ. An evaluation of semiconductor and ionization chamber detectors for diagnostic x-ray dosimetry measurements. Phys. Med. Biol. 2007; 52; 4465–4480.

McKeever SWS, Moscovitch M, Townsend PD. Thermoluminescence Dosimetry Materials – Property and Uses. Ashford: Nuclear Technology Publishing; 1994.

Meyer P, Regal R, Jung M, Siffert P, Mertz L, Constantinesco A. Feasibility of a semiconductor dosimeter to monitor skin dose in interventional radiology. Med. Phys. 2001; 28: 2002–2006.

Muhogora WE, Devetti A, Padovani1 R, Msaki R, Bonutti F. Application of European protocol in the evaluation of contrast-to-noise ratio and mean glandular dose for two digital mammography systems. Rad. Prot. Dosim. 2008; 129 (1–3): 231–236.

National Radiological Protection Board (NRPB), Institute of Physical Sciences in Medicine and College of Radiographers. National Protocol for Patient Dose Measurements in Diagnostic Radiology. Chilton: NRPB, 1992.

Obenauer S, Hermann K-P, Grabbe E. Dose reduction in full-field digital mammography: an anthromorphic breast phantom study. Br. J. Radiol. 2003; 76: 478–482.

Pöyry P, Komppa T, Kosunen A. Calibration of dose-area product meters for diagnostic X-ray beams. In: Proc. XXXIX Annual Conf. of the Finnish Physical Society, Report series in Helsinki University of Technology Laboratory. Espoo: Otamedia; 2005; p. 247.

Pöyry P, Komppa T, Kosunen A. X-ray beam quality specification for kerma area product meters. In: Book of extended synopses. IAEA-CN-146. Int. Conf. on Quality Assurance and New Techniques in Radiation Medicine. Vienna: IAEA; 2006a. pp 298–299.

Pöyry P, Komppa T, Kosunen A. A tandem calibration method for kerma-area product meters. In: Book of extended synopses. IAEA-CN-146. Int. Conf. on Quality Assurance and New Techniques in Radiation Medicine. Vienna: IAEA; 2006b. pp 290–291.

Pöyry P, Zanca F, Bosmans H. Experimental investigation of the necessity for extra flat field corrections in quality control of digital mammography. International Workshop on Digital Mammography. In: Astley S. et al. (eds.). IWDM 2006, LNCS 4046. Berlin Heidelberg: Springer-Verlag; 2006c. pp. 475–481.

Rannikko S, Karila KTK, Toivonen M. Patient and population doses of x-ray diagnostics in Finland. STUK-A144. Helsinki: Radiation and Nuclear Safety Authority; 1997.

Shrimpton PC, Wall BJ. 1982 An evaluation of the Diamentor transmission ionisation chamber in indicating exposure-area product (R cm2) during diagnostic radiological examinations. Phys. Med. Biol. 1982; 29: 871–878.

Shrimpton PC, Wall BJ, Jones DJ, Fisher ES. The measurement of energy imparted to patients during x-ray examinations using the Diamentor exposure-area product meter. Phys. Med. Biol. 1984; 29 (10): 1199–1208.

STM–Ministery of Social Affairs and Health. Decree of the Ministry of Social Affairs and Health on the medical use of radiation, 10.5.2000/423, Helsinki, 2000.

STUK–Radiation and Nuclear Safety Authority. Röntgentutkimuksesta potilaalle aiheutuvan säteilyaltistuksen määrittäminen. STUK tiedottaa 1/2004 (Assessing patient dose in diagnostic radiology. STUK bulletin 1/2004), Helsinki: Radiation and Nuclear Safety Authority; 2004. (In Finnish)

Tapiovaara M. Image quality measurements in radiology Rad. Prot. Dosim. 2005; 117 (1–3): 116–119.

Tapiovaara M. Relationships between Physical Measurements and User Evaluation of Image Quality in Medical Radiology – a Review. STUK-A219. Helsinki: Radiation and Nuclear Safety Authority; 2006.

Tapiovaara M, Siiskonen T. PCXMC, A Monte Carlo program for calculating patient doses in medical x-ray examinations. 2nd Ed. STUK-A231. Helsinki: Radiation and Nuclear Safety Authority; 2008.

Tapiovaara M, Tapiovaara T. Spetripaja (2.0) -ohjelman käyttöohje ja validointi. (The validation and user's manual of the Spektripaja (2.0) program). STUK-TR 3. Helsinki: Radiation and Nuclear Safety Authority; 2008. (In Finnish)

Toroi P, Komppa T, Kosunen A. Measurement of dose-area product. Calibration of DAP meters in x-ray beams. STUK-TR 4. Helsinki: Radiation and Nuclear Safety Authority; 2008. (In Finnish)

Tucker DM, Rezentes PS. The relationship between pixel values and beam quality in photostimulable phosphor imaging. Med. Phys. 1997; 24(6): 887–893.

Vano E, Fernandez JM. Patient dose management in digital radiography. Biomedical Imaging Intervention Journal 2007; 3(2):e26.

Vano E, Fernandez JM, Ten JI Guibelalde E, Gonzalwz L, Pedrosa CSA. Real-time measurement and audit of radiation dose to patients undergoing computed radiography. Radiology 2002; 225(1): 283–288.

Vano E et.al. Patient dose in interventional radiology: A European survey Rad. Prot. Dosim. 2008a; 129: 39–45.

Vano E, Martinez D, Fernandez J M, Ordiales J M Prieto C, Floriano A, Ten J I. Paediatric entrance doses from exposure index in computed radiography. Phys. Med. Biol. 2008b; 53: 3365–3380.

Vano E, Ubeda C, Leyton F, Miranda P. Radiation dose and image quality for paediatric interventional cardiology. Phys. Med. Biol. 2008c; 53: 4049–62.

Venkatakrishnan V, Yavuz M, Niklason LT, Opsahl-Ong B, Han S, Landberg C, Nevin R, Hamberg L, Kopans D. Experimental and theoretical spectral optimization for digital mammography. In: Proceedings of the SPIE 3659. 1999: 142–149.

Wagner LK, Fontenla DP, Kimme-Smith C, Rothenberg LN, Shepard J, Boone JM. Recommendations on performance characteristics of diagnostic exposure meters: Report of AAPM Diagnostic X-Ray Imaging Task Group No. 6. Med. Phys. 1992; 19: 231–241.

Warren-Forward H M, Duggan L. Towards in vivo TLD dosimetry in mammography. Br. J. Radiol. 2004; 77: 426–432.

Williams MB et al. Optimization of exposure parameters in full field digital mammography. Med. Phys. 2008; 35(6): 2414–2423.

Witzani J et. al. Calibration of dosemeters used in mammography with different x ray qualities: Eu-romet project NO. 526. Rad. Prot. Dosim. 2004; 108: 33–45.

Young KC, Oduko JM, Bosmans H, Nijs K, Martinez L. Optimal beam quality selection in digital mammography. Br. J. Radiol. 2006; 79: 981–990.

Zanca F, Jacobs J, Pöyry P, Van Ongeval C, Carton, AC, Deprez T, Marchal G, Bosmans H. Development and implementation of a user friendly and automated environment for creation of databases of digital mammograms with simulated microcalcifications. In: Jiang Y, Eckstein MP. (Eds.). Image perception, observer performance, and technology assessment. Proceedings of SPIE (The International Society for Optical Engineering) Medical Imaging, 2006.

Zoetelief J, Julius HW, Christensen P. Recommendations for Patient Dosimetry in Diagnostic Radiology Using TLD. Rep. EUR 19604. Luxembourg: European Commission; 2000.

I

TOROI P, KOMPPA T, KOSUNEN A (2008):
A tandem calibration method for
kerma-area product meters.
Phys. Med. Biol. 53: 4941–4958.

II

TOROI P, KOMPPA T, KOSUNEN A, TAPIOVAARA M (2008):
Effects of radiation quality on the calibration of kerma-area product meters in x-ray beams.
Phys. Med. Biol. 53: 5207–5221.

III

TOROI P, KOSUNEN A (2009):
The energy dependence of the response of a patient dose calibrator.
Phys. Med. Biol. 54: N151–N156.

IV

TOROI P, NIEMINEN M, TENKANEN-RAUTAKOSKI P, VARJONEN M (2009):
Determining air kerma from pixel values in digital mammography.
Phys. Med. Biol. 54: 3865–3879.

V

TOROI P, ZANCA F, YOUNG KC, VAN ONGEVAL C, MARCHAL G, BOSMANS H (2007):
Experimental investigation on the choice of the tungsten/rhodium anode/filter combination for an amorphous selenium-based digital mammography system.
European Radiology 17 (9): 2368–2375.

STUK-A reports/STUK-A-sarjan julkaisuja

STUK-A239 Toroi P. Patient exposure monitoring and radiation qualities in two-dimensional digital x-ray imaging. Helsinki 2009.

STUK-A238 Ilus E. Environmental effects of thermal and radioactive discharges from nuclear power plants in the boreal brackish-water conditions of the northern Baltic Sea. Doctoral thesis. Helsinki 2009.

STUK-A237 Arvela H, Reisbacka H. Radonsanering av bostäder. Helsinki 2009.

STUK-A236 Saxén R, Rask M, Ruuhijärvi J, Vuorinen P, Rantavaara A, Koskelainen U. 137Cs in small forest lakes of Finland after the Chernobyl accident. Helsinki: Radiation and Nuclear Safety Authority; 2009.

STUK-A235 Mustonen R, Sjöblom K-L, Bly R, Havukainen R, Ikäheimonen T. K, Kosunen A, Markkanen M, Paile W. Säteilysuojelun perussuositukset 2007. Suomenkielinen lyhennelmä julkaisusta ICRP-103. Helsinki 2009.

STUK-A234 Belyakov O (Ed.). Non-targeted effects of ionising radiation. Proceedings of the RISC-RAD specialised training course “Non-targeted effects of ionising radiation”. STUK – Radiation and Nuclear Safety Authority, Helsinki, Finland 14–16 February 2005. Helsinki 2008.

STUK-A233 Arvela H, Valmari T, Reisbacka H, Niemelä H, Oinas T, Mäkeläinen I. Radontalkoot – Tilannekatsaus 2008. Helsinki 2008.

STUK-A232 Kiljunen T. Patient doses in CT, dental cone beam CT and projection radiography in Finland, with emphasis on paediatric patients. Helsinki 2008

STUK-A231 Tapiovaara M, Siiskonen T. PCXMC. A Monte Carlo program for calculating patient doses in medical x-ray examinations. Helsinki 2008

STUK-A230 Salomaa S, Sirkka L. (toim.), Tutkimushankkeet 2006-2008. Helsinki 2008

STUK-A229 Arvela H, Reisbacka H. Asuntojen radonkorjaaminen. Helsinki 2008

STUK-A228 Toivonen H, Lahtinen J, Pöllänen R (toim.). Säteilyyn liittyvät uhkakuvat - Ydinvoimalaturma. Helsinki 2008

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STUK-A224 Kuukankorpi S, Toivonen H, Moring M, Smolander P. Mobile Spectrometry System for Source Finding and Prompt Reporting. Helsinki 2007.

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STUK-A222 Hutri K-L. An approach to palaeoseismicity in the Olkiluoto (sea) area during the early Holocene. Helsinki 2007.

STUK-A221 Valmari T, Arvela H, Reisbacka H. Päiväkotien radonkartoitus. Helsinki 2007.

STUK-A220 Karppinen J, Järvinen H. Tietokonetomografialaitteiden käytön optimointi. Helsinki 2006.

STUK-A219 Tapiovaara M. Relationships between physical measuments and user evaluation of image quality in medical radiology – a review. Helsinki 2006.

STUK-A218 Ikäheimonen TK, Klemola S, Ilus E, Varti V-P, Mattila J. Monitoring or radionuclides in the vicinities of Finnish nuclear power plants in 1999–2001. Helsinki 2006.

STUK-A217 Ikäheimonen TK (toim.). Ympäristön radioaktiivisuus Suomessa – 20 vuotta Tshernobylista. Symposium Helsingissä 25.–26.4.2006. Helsinki 2006.

STUK-A216 Pastila R. Effect of long-wave UV radiation on mouse melanoma: An in vitro and in vivo study. Helsinki 2006.

STUK-A215 Rantavaara A. Elintarvikeketjun suojaustoimenpiteet laskeumatilanteiden varalle. Helsinki 2005.

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