Code of practice for personal dosimetry of professionals wearing protective clothing during radiological procedures

NEDERLANDSE COMMISSIE VOOR STRALINGSDOSIMETRIE

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Preface

The Netherlands Commission on Radiation Dosimetry (Nederlandse Commissie voor Stralingsdosimetrie, NCS) was officially established on September 3rd, 1982 with the aim of promoting the appropriate use of dosimetry of ionising radiation both for scientific research and for practical applications. The NCS is chaired by a board of scientists, installed upon the suggestion of the supporting societies, including the Netherlands Society for Radiotherapy and Oncology (Nederlandse Vereniging voor Radiotherapie en Oncologie), the Dutch Society of Nuclear Medicine (Nederlandse Vereniging voor Nucleaire Geneeskunde), the Dutch Society for Medical Physics (Nederlandse Vereniging voor Klinische Fysica), the Netherlands Radiobiological Society (Nederlandse Vereniging voor Radiobiologie), the Society of Radiological Protection of The Netherlands (Nederlandse Vereniging voor Stralingshygiëne), the Dutch Society for Medical Imaging and Radiotherapy (Nederlandse Vereniging Medische Beeldvorming en Radiotherapie), the Radiological Society of The Netherlands (Nederlandse Vereniging voor Radiologie), the Belgian Hospital Physicists Association (Belgische Vereniging voor Ziekenhuisfysici/Société Belge des Physiciens des Hôpitaux) and the Dutch society of technicians and other specialists in the field of medical physics (Nederlandse Vereniging van Klinisch Fysisch Medewerkers).

To pursue its aims, the NCS accomplishes the following tasks: participation in dosimetry standardisation and promotion of dosimetry intercomparisons, drafting of dosimetry protocols, collection and evaluation of physical data related to dosimetry. Furthermore, the commission shall maintain or establish links with national and international organisations concerned with ionising radiation and promulgate information on new developments in the field of radiation dosimetry.

Code of practice for personal dosimetry of professionals wearing protective clothing during radiological procedures

Prepared by the Subcommittee “Loodschorten” (lead aprons) of the Netherlands Commission on Radiation Dosimetry (NCS) for the Dutch Ministry of Social Affairs and Employment (SZW), contract ARBO/M&A/2005/94066.

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*Members of the subcommittee represent the five approved Dutch dosimetric services and various professional organizations (KNMvD, NCS, NVMBR, NVKF, NVS). To promote the widespread acceptance and application of the code of practice presented in this publication, representatives of other related professional groups (NVvR, NVVC), united in the Advisory Platform Radiology and Nuclear Medicine (NCS Platform voor Radiologie en Nucleaire Geneeskunde), have also been consulted.

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User's Guide / Leeswijzer

The code of practice is given in Chapter 5, which is the most relevant chapter from the user's point of view.

The code of practice is focused on the group of health care workers with relatively high potential exposure, i.e. those active in interventional radiology/cardiology. It is assumed that the workers wear aprons, which offer protection by relying on lead-based materials. The code of practice is not valid for lead-free materials.

Chapters 1 through 3 offer to a larger extent relevant background information that underpins the recommendations. They also introduce the necessary basic quantities and units.
In Chapter 4 a number of alternatives is described, including advantages and drawbacks, which have been considered during the development of the code of practice.

De aanbevelingen in de vorm van een code of practice worden gegeven in Hoofdstuk 5, het meest relevante hoofdstuk gezien vanuit de gebruiker.

Dit rapport richt zich op de beroepsgroep in de gezondheidszorg met een potentieel hoge blootstelling aan straling, te weten zij die werkzaam zijn in de interventieradiologie/-cardiologie. Er wordt uitgegaan van het dragen van schorten, waarvan de beschermende werking berust op loodhoudend materiaal. Het protocol geldt niet voor loodvrije materialen.

In de hoofdstukken 1 tot en met 3 wordt de achtergrondinformatie gegeven die bepalend is geweest voor de gemaakte keuzes. Hierin worden onder andere ook de benodigde basisgrootheden en eenheden geïntroduceerd.
In Hoofdstuk 4 wordt een aantal alternatieven besproken, met hun voor- en nadelen, die bij het tot stand komen van het aanbevolen protocol de revue zijn gepasseerd.

Summary

Dutch legislation (Besluit stralingsbescherming), implementing the EU Council Directive 96/29/Euratom, requires record keeping of the effective dose to employees who may be exposed to more than 1 mSv ionising radiation per year. In current practice, readings from personal dosemeters ($H_P(10)$) are recorded in the national database (NDRIS) as an estimator of effective dose. However, the effective dose to professionals who wear protective clothing during exposure will be appreciably lower than $H_P(10)$ measured outside the apron. It is not unusual that individual employees of certain highly exposed categories apparently exceed the annual dose limit when the dose is based on such measurements. To improve the estimation of effective dose some national dosimetric services apply a conversion factor to the readings before registration in NDRIS whereas others do not. This makes comparison of recorded doses difficult. Hence it is highly desirable to apply safe standard protocols to harmonise the interpretation of measured dose values. An important condition is that such protocols should balance correctness and simplicity to promote their acceptance and application by fieldworkers, local radiation safety officers, dosimetric services and the government.

The purpose of the research project that the NCS subcommittee “Loodschorten” (lead aprons) has carried out for the Dutch Ministry of Social Affairs and Employment is to derive protocols for proper personal dosimetry when protective clothing is worn. Questions that are to be answered comprise the current situation in the Netherlands and abroad; how to estimate effective dose best from the dosemeter reading; which categories of professionals/activities are involved; under which circumstances correction of dose values should be allowed and what conversion factor then should be applied; and, finally, what is the optimal wearing position of the dosemeter. Recommendations resulting from the study are discussed and presented in the current report.

Concisely, the following is recommended. One group of professionals is identified with a high risk of exceeding the annual dose limit when personal dosemeters are not corrected. This is the group of health care workers in interventional radiology/cardiology. When performing routine medical procedures it would be sufficient to wear a single personal dosemeter. That dosemeter should be worn at a central position high on the chest and outside the apron. Depending on the thickness of the lead apron, and the presence or absence of a thyroid collar, a conversion factor varying in the range of 5 to 15 can be selected. The dosemeter reading must be divided by this factor to yield a reasonable estimate of effective dose. Both the converted and original dose are to be recorded in NDRIS.

Samenvatting

Nederlandse regelgeving (Besluit stralingsbescherming) volgt de EU Richtlijn 96/29/Euratom en verplicht het registreren van de effectieve dosis bij werknemers, bij wie de effectieve dosis door beroepsmatige blootstelling aan ioniserende straling groter kan zijn dan 1 mSv per jaar. In de praktijk wordt de uitlezing van een persoonsdosismeter ($H_P(10)$-waarde) opgenomen in het nationale gegevensbestand (NDRIS). Bij blootgestelde werknemers die beschermende kleding dragen, zoals loodschorten, zal een buiten de schort bevestigde persoonsdosismeter een te hoge waarde aangeven. Het komt voor dat werknemers uit groepen met hoge blootstelling hun jaarlijkse dosislimiet overschrijden, wanneer die uitsluitend wordt gebaseerd op dergelijke metingen. Voor een betere schatting van de effectieve dosis past een aantal dosimetriediensten dan een conversiefactor toe alvorens de dosis in NDRIS te registreren. Andere doen dit echter niet, waardoor het lastig is om dosisregistraties onderling te vergelijken. Het is gewenst, om tot een nationaal protocol te komen, dat voorschrijft hoe de persoonsdosimetrie moet geschieden bij blootgestelde werknemers met beschermende kleding. Een dergelijk protocol moet een goed compromis zijn tussen correctheid (juiste dosis) en eenvoudige toepasbaarheid. Dit laatste in verband met brede acceptatie door werknemers, (lokale) stralingsbeschermingseenheden, dosimetriediensten en de overheid.

Het doel van het onderzoeksproject dat de NCS subcommissie “Loodschorten” heeft uitgevoerd voor het Ministerie van Sociale Zaken en Werkgelegenheid is het opstellen van een geschikt protocol. Tot de te beantwoorden vragen behoren: wat is de huidige situatie in Nederland en in het buitenland; hoe kan de effectieve dosis het best worden bepaald met persoonsdosismeters; om welke categorieën werknemers en activiteiten gaat het; wanneer en hoe moet er worden gecorrigeerd; en wat is de optimale draagpositie van de persoonsdosismeter. De aanbevelingen die uit deze studie zijn voortgekomen worden in dit rapport beargumenteerd gepresenteerd.

Samenvattend worden de volgende aanbevelingen gedaan. Er is een groep blootgestelde werknemers die het risico loopt dat de jaarlijkse dosislimiet wordt overschreden als geen wijziging wordt toegepast op de uitlezing van de dosismeter. Dit is de groep van blootgestelde werknemers in de interventieradiologie/-cardiologie. Bij routinematige uitvoering van medische procedures volstaat het dragen van een enkele persoonsdosismeter. Deze moet worden gedragen op een positie in het midden van en hoog op de borst, buiten het loodschort. Afhankelijk van de loodschortdikte en het wel dan niet dragen van een schildklierkraag kan een conversiefactor worden geselecteerd met een waarde tussen de 5 en de 15. De uitlezing van de dosismeter moet worden gedeeld door

deze conversiefactor. Dat levert dan een redelijke schatting voor de effectieve dosis. Zowel de gewijzigde als de oorspronkelijk gemeten dosis wordt in NDRIS geregistreerd.

Abbreviations and Acronyms

ADS	Approved dosimetric service
ALARA	As low as reasonably achievable
AP	Antero-posterior
APD	Active personal dosemeter
ASD	Atrial septal defect
Bs	[Besluit stralingsbescherming] Dutch Decree on Radiation Protection
BSS	Basic safety standards
CONRAD	EC Coordinated Network for Radiation Dosimetry
DAP	Dose area product
DBC	[diagnose-behandelingscombinatie] diagnosis treatment combination
EC	European Commission
EDPG	External Dosimetry Program Guide
EPD	Electronic personal dosemeter
Erasmus MC	Erasmus University Medical Centre, Rotterdam
ESOREX	European study of occupational radiation exposure
EU	European Union
EURADOS	European Radiation Dosimetry Group
HSE	Health and Safety Executive (UK)
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
IR	Interventional radiology
KCL	[Stichting Klinisch Chemisch Laboratorium]
KNMvD	[Koninklijke Nederlandse Maatschappij voor Diergeneeskunde] Royal Netherlands Veterinary Association
LAT	lateral
LUMC	Leiden University Medical Center
MC	Monte Carlo
NCRP	National Council on Radiation Protection and Measurements
NCS	[Nederlandse Commissie voor Stralingsdosimetrie] Netherlands Commission on Radiation Dosimetry
NDRIS	National Dose Registration and Information System
NRC	Nuclear Regulatory Commission
NRG	Nuclear Research and consultancy Group
NTA	Nuclear track analysis

NVKF	[Nederlandse Vereniging voor Klinische Fysica] Dutch Society for Medical Physics
NVMBR	[Nederlandse Vereniging Medische Beeldvorming en Radiotherapie] Dutch Society for Medical Imaging and Radiotherapy
NVS	[Nederlandse Vereniging voor Stralingshygiëne] Society of Radiological Protection of The Netherlands
NVVC	[Nederlandse Vereniging voor Cardiologie] Netherlands Society of Cardiology
NVvR	[Nederlandse Vereniging voor Radiologie] Radiological Society of The Netherlands
PA	postero-anterior
PBM	[Persoonlijk beschermingsmiddel] Personal protective equipment
PPE	Personal protective equipment
PTA	Percutaneous transluminal angioplasty
RF	Radiofrequency
RIVM	[Rijksinstituut voor Volksgezondheid en Milieu] National Institute for Public Health and the Environment
RPA	Radiation protection advisor [algemeen coördinerend stralingsdeskundige]
RPL	Radiophotoluminescence
RPO / RSO	(Local) radiation protection office(r) / radiation safety office(r) [stralingsdeskundige op de afdeling]
SBE	[Stralingsbeschermingseenheid] Radiation Protection Unit
SZW	[Ministerie van Sociale Zaken en Werkgelegenheid] Dutch Ministry of Social Affairs and Employment
TL(D)	Thermoluminescence (Dosemeter)
TUDelft	[Technische Universiteit Delft] Delft University of Technology
TU/e	[Technische Universiteit Eindhoven] Eindhoven University of Technology
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UU	Utrecht University
VM	Veterinary medicine
VUmc	[Vrije Universiteit Medisch Centrum] Free University Medical Center, Amsterdam
WP	Work package

List of Symbols

CF	Conversion factor
D_T	Organ dose
$D_{T,R}$	Dose to organ T due to radiation type R
E	Effective dose
F	A divider (effective dose equals dosemeter reading divided by F)
H_m	Measured dose value
$H_P(d)$	Personal dose equivalent (in tissue at d mm below a specified point on a surface), also referred to by the obsolete names individual dose equivalent, penetrating for d in the order of 10 mm and individual dose equivalent, superficial ($H_S(d)$) for d typically equal to 0.07 mm
$H_{P,NCS}$	$H_P(10)$ value as measured, then modified according to the current NCS code of practice
H_T	Equivalent organ dose, i.e. organ dose corrected for the type of radiation
H*(d)	Ambient dose equivalent
H'(d)	Directional dose equivalent
H_s	$H_P(10)$ measured under the apron (shielded dosemeter)
H_u	$H_P(10)$ measured outside the apron (unshielded dosemeter)
K_a	Air Kerma free in air
M	A multiplier (effective dose equals dosemeter reading multiplied by M)
w_R	Radiation weighting factor
w_T	Tissue weighting factor

1. Introduction

1.1 Individual monitoring, EU Directive and Dutch legislation

In many European and North American countries individual monitoring, i.e. regular dose measurement and dose registration, is mandatory when the exposure of professionals to ionising radiation is likely to exceed a certain threshold value. In Europe, Council Directive 96/29/Euratom [1] requires that Member States of the European Union (EU) implement measures for the protection of exposed employees in their national legislation. Most Member States have complied. In The Netherlands, for example, a decree on radiological protection was formulated (Besluit stralingsbescherming (Bs) [2]), which became effective in 2002. Sections 76-102 of the decree deal with occupational exposure, e.g. how it should be determined and how data should be recorded. The threshold above which an exposed employee has to participate in an individual monitoring programme was set at an effective dose level of 1 mSv in a year.

To provide an overview of the radiation protection infrastructure existing in the EU Member States, the ESOREX initiative (European Study of Occupational Radiation Exposure 1997-2000) was started [3]. It comprised a qualitative information survey and a quantitative data survey, first for West European and later also for East European countries. For each country a document was prepared containing general information, e.g. on the number of professionals that is monitored, in total and individually; the legislation; the dose quantities and dose limits; the rules for monitoring; the approved dosimetric services (ADS); and the dose registration policy. These documents, for instance the Dutch one [4], can be downloaded from the ESOREX web site (http://www.esorex.cz). They may be helpful for harmonisation purposes. As new Member States have entered the EU a follow-up of the study was necessary (ESOREX2005), which also aimed at surveying the various personal monitoring systems in use and to provide information on occupational radiation doses.

In the USA requirements for occupational radiation protection were specified and added to the Code of Federal Regulations in 1998 (10 CFR 835 [5]). In 1999 the US Department of Energy issued a guide for the practical application of the rules (EDPG [6]).

Purposes of individual monitoring include the possibility to

- demonstrate compliance with regulatory requirements, e.g. that the principle of ALARA (as low as reasonably achievable) is fulfilled and that dose limits have not been exceeded.
- provide information in the case of accidental exposure.

- alert when an action dose level has been exceeded.
- perform statistical analyses and to detect trends, e.g. changes in the radiation environment.
- compare procedures concerning radiological protection and select the optimal one.
- assess the probability that possible health problems of an employee might be associated with previous exposure to radiation.
- collect basic information for medical and legal assurance for employer and employee should the latter experience late effects of radiation. For this reason records of individual doses should be kept for at least 30 y after he/she has quitted his/her job or until the employee has reached or would have reached the age of 75.

1.2 Dose registration in The Netherlands: NDRIS

In The Netherlands the registration of the results of individual monitoring has been centralised since 1989 in a national database, the National Dose Registration and Information System (NDRIS), which NRG-Arnhem operates for the Dutch Ministry of Social Affairs and Employment (SZW) (Van Dijk [7]). In 2001 the number of registered exposed employees in active service was 34,000. Records of more than 100,000 persons are kept. A schematic diagram of the parties involved in NDRIS is shown in Fig. 1.

The vast majority of data is supplied by the approved dosimetric services. Additional data is obtained from electronic dosemeters monitoring the workplace in the Dutch nuclear power plant, from calculated aircrew exposure, and from reports on individual doses due to exposure during work done in facilities abroad. Also data on exposure due to internal contamination with radionuclides is entered.

Next to technical-administrative data, information is also kept about the age, gender, employer category and the nature of the radiological activities of the employee. Currently, the categorisation of employees is subject of debate and a new classification system is proposed (Table 1) based on recommendations of several international bodies (EC, UNSCEAR) and experience within national registers abroad (Van Dijk *et al.* [8,9]). The new classification is three-dimensional, i.e. it codes for the type of employer (e.g. hospital, nuclear power plant, educational institution), the type of application (medical, commercial, nuclear fuel cycle, other; each with subcategories, e.g. commercial – aviation, cabin crew) and the type of radiation source (e.g. linear accelerator, reactor, natural source). In particular the addition of

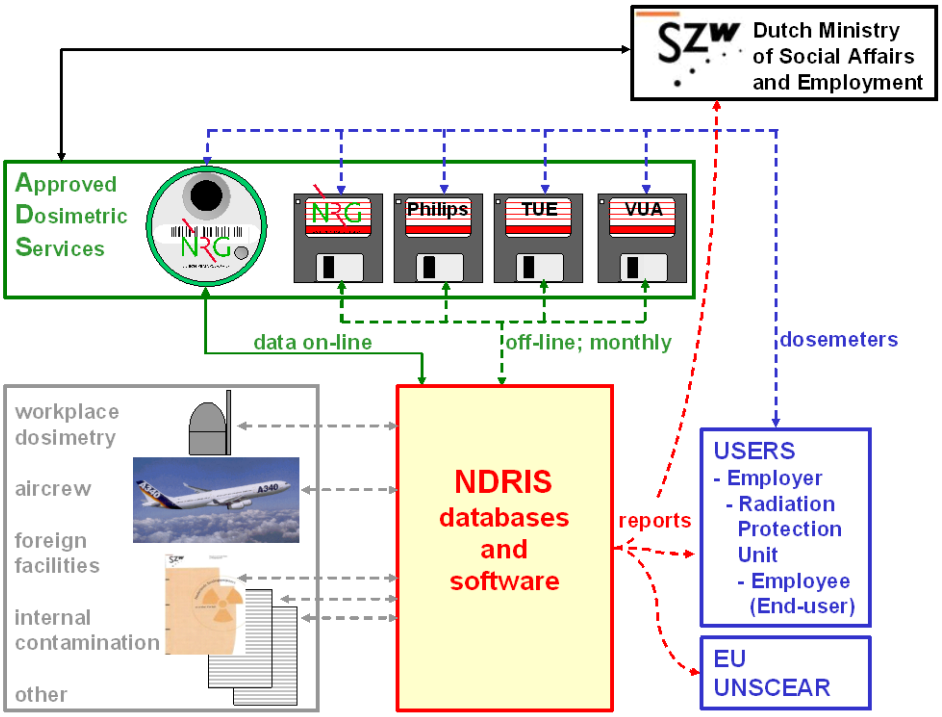

Fig. 1 The National Dose Registration and Information System and parties involved in individual monitoring in The Netherlands.

the last dimension is expected to create more clearness to the users of dosemeters and increase the usefulness of NDRIS with respect to the interpretation of the statistical reports.

This leaves unchanged that dosemeter readings and cumulative dose are recorded periodically. Several types of overview are produced for the various well-defined parties that have an established interest in the information (De Jong [10]).

In general, either the employer or the approved dosimetric services provide the dosemeter readings to be recorded in NDRIS. Once put into the system the dose readings cannot be changed easily. Rectifications are allowed only in the case of obvious mistakes and only after permission by the labour inspectorate (“Arbeidsinspectie”) of the Ministry of SZW.

An important aspect of storing personal dose information in a national database is that a professional’s personal dose history can always be retrieved, also long after e.g. migration to another employer, a temporary post abroad, merging / splitting or liquidation of an organization, etc.

Table 1 Categories of exposed professionals who apply for individual monitoring (based on [9]).

At present		Proposed		
Branch	**Professional group**	**Employer**	**Application**	**Equipment**
Health Care	diagnostic radiology, general X-ray and mammography	Hospital, non-university	MEDICAL	X-ray machine, <100 kVp
	diagnostic radiology, cardiology	Hospital, university	general radiology	X-ray machine, ≥100 kVp
	diagnostic radiology, surgical	Dental practice	fluoroscopy, physician	X-ray leakage, e.g. radar
	diagnostic radiology, dentistry	Veterinary practice	fluoroscopy, other	Linear accelerator
	diagnostic radiology, veterinary medicine	Other medical	radiotherapy	Cyclotron
	therapy, external	Nuclear power plant	nuclear medicine, excl. PET	Reactor
	therapy, other	Research reactor	PET	Encapsulated source, excl. neutron
	in vivo examination	Business/Industry	dental radiology	Encapsulated neutron source
	outside laboratory	Educational	veterinarian radiology	Encapsulated source, combined
	other nuclear medicine	Public services	other medical	Open source, C/D level
	other medical	Government, Inspectorate	NUCLEAR FUEL	Open source, B level
Nuclear Industry	reactor, own personnel	Defence	Enrichment	Natural source
	reactor, external personnel	Other	Nuclear power, own personnel	Other equipment
	enriched uranium		Nuclear power, external personnel	
	other nuclear industry		Dismantlement	
Business	non-destructive exam., fixed		Nuclear waste	
	non-destructive exam., mobile		Storage	
	X-ray equipment		Transport	
	isotope production		Research	
	radiochemistry		Other	
	other business		BUSINESS	
Aviation	-		Radiography, fixed	
			Radiography, mobile	
Radiation protection, research, education, other	radioprotection		Transport (excl. nuclear fuel)	
	research, education		Isotope production	
	other applications		Irradiation	
			Mining (incl. oil/gas)	
			Measurement & Control	
			Air crew, flightdeck personnel	
			Air crew, cabin personnel	
			Other	
			OTHER APPLICATIONS	
			Research, development, education	
			Maintenance, repair	
			Security, safety, inspectorate	
			Other	

1.3 Dosimetric services

In The Netherlands five approved dosimetric services (ADS) distribute and collect personal dosemeters to measure exposure of end-users in organizations and laboratories. These are NRG Radiation & Environment, Arnhem (http://www.dosimetrie.nl); NRG, Petten; Persoonsdosimetriedienst VUmc, Amsterdam; Philips Stralingsbeschermingsdienst, Eindhoven (http://www.sbd.philips.com); and Stralingsbeschermingsdienst TU/e, Eindhoven (http://w3.tue.nl/nl/diensten/sbd/).
Monitoring frequency may vary with the expected magnitude of exposure. Although 4-weeks intervals are most common, 2-weeks and 3-months intervals also occur. It is good practice that the dosimetric services send periodical (e.g. monthly) overviews of dose data to their clients and that an immediate warning is given when a dose limit has been exceeded or when an unusual dose increase larger than 1 mSv is observed. A few ADS take care that, when redistributed, the personal dosemeters will go at random (but always in a traceable way) to different end-users, to prevent any systematic under- or overestimation of personal dose.

In other countries issuing and keeping record of personal dosemeters is done in a similar way. For instance in the UK the Health and Safety Executive (HSE) is the legal organisation that appoints the ADS that employers can turn to.

1.4 Dose equivalent, effective dose and dose limits

When an organ, T, is exposed to a certain type of radiation the absorbed dose, D_T, to that organ is the average energy deposited in the organ divided by the organ mass. It has the unit gray (Gy = J kg^{-1}). Equivalent dose, H_T, can be obtained by multiplying the absorbed dose by a radiation weighting factor, w_R. The radiation weighting factor takes into account that equal doses of different types of radiation may cause detrimental effects to different degree in a tissue. The unit of equivalent dose is the sievert (Sv = J kg^{-1}).

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

Effective dose, E, is a weighted sum of doses to relevant organs at risk. Depending on the organ a tissue weighting factor, w_T, is applied to the equivalent dose. This tissue weighting factor takes into account that different organs show a different susceptibility when exposed to the same dose equivalent.

$$E = \sum_T w_T \cdot H_T \qquad (2)$$

The concept of effective dose was introduced by the International Commission on Radiological Protection (ICRP, Publication 60 [11]). Numerical values for the weighting factors and more detailed information about the computation of E can be found in that publication. (It should be mentioned that the ICRP is currently preparing a revision of the tissue weighting factors, e.g. the eye lens seems to be more radiosensitive than previously assumed.)

Effective dose is related to so-called stochastic risks of the exposure to ionising radiation, i.e. induction of (fatal) tumours and hereditary effects in offspring. Arguably it is the most suitable dosimetric quantity in relation to the stochastic risk. Therefore, dose limits are usually expressed in terms of effective dose. For deterministic effects, i.e. (functional) damage to certain tissue types (e.g. skin burns, cataract) dose limits are expressed in equivalent dose.

In The Netherlands, the annual dose limit for stochastic effects in exposed professionals has been set at 20 mSv. The yearly equivalent dose must remain below or equal to 150 mSv for the eye lens, 500 mSv for the skin (averaged over any cm^2) and 500 mSv for the extremities (hands and lower arms, ankles and feet) (Bs [2]).

1.5 Operational and limiting quantities

For the calculation of effective dose it is necessary to know the doses to the organs at risk. Unfortunately it is almost impossible to measure organ doses directly. Hence, so-called operational quantities have been introduced that serve as usable substitutes.

Operational quantities are quantities used in radiological protection practice that are measurable with simple monitoring instruments and that provide sufficient conservative assessment of limiting quantities to ensure absence of underestimates (Harder [12]). Limiting quantities are quantities in terms of which effective dose and dose equivalent limits have been, or are recommended to be, expressed.

In the present case, the operational quantity “personal dose equivalent” ($H_P(10)$, see below) is used to assess the limiting quantity, effective dose (E). It has been derived that $H_P(10)$, measured with a personal dosemeter at an appropriate place on the body, gives an adequate indication of E (ICRP-75 [13]).

1.6 Questions to be answered

Considering the wide range of exposure conditions (e.g., workplace geometry, radiation beam quality, fields with primary and scattered radiation, nature of professinal activities and protective measures), the following questions arise:

- How to determine $H_P(10)$?
- How well does a measured value of $H_P(10)$ represent E?
- What if protective clothing is worn?

Personal dosemeters that are nowadays available for external photon fields in the workplace often will indicate $H_P(10)$ reasonably well, at least when unshielded and in conditions of rather uniform fields and photon energy in excess of 40 keV. Variation in indications of different equally exposed dosemeters mostly remains within ±20%. (e.g. Lopez Ponte *et al.* [14]; Bolognese *et al*. [15]; NCRP-122 [16]).

A widely accepted requirement is that a measured dose value (H_m, e.g. nominally in terms of $H_P(10)$) should be within a factor of 1.5 from the true dose, or $0.67 \leq H_m / H_P(10) \leq 1.5$. For monthly values of $H_P(10)$ below 10 mSv this requirement can be gradually decreased to larger allowed deviations, e.g. $0.5 \leq H_m / H_P(10) \leq 1.7$ for $H_P(10)$=0.5 mSv (Böhm [17]). Thus, the personal dosemeters seem to be more than adequate.

When the professional is exposed to radiation that cannot be considered a broad and/or unidirectional beam, it may become difficult to assure that the above requirement is met. Furthermore, it cannot be maintained that in those circumstances $H_P(10)$ always is an adequate estimate of effective dose, E. When the professional is wearing protective clothing, i.e. an apron, and possibly a thyroid collar, of lead equivalent material, the relation between H_m and E becomes even more complicated and the position of the personal dosemeter becomes very important.

A dosemeter worn under the apron may indicate too low with respect to E –because any unshielded parts of the exposed employee (like head and arms) are not taken into account– and with relatively large uncertainty because of its usually small sensitivity in the low dose range. A dosemeter worn outside the apron will indicate too high with respect to E because it does not take into account the protective effect of the apron.

In contrast to e.g. the UK and Switzerland, where a dosemeter is usually worn under the apron (HSE [18], Dosimetrieverordnung [19]), in The Netherlands dosemeters are usually worn outside the apron (De Jong and Van Dijk, [20]). Before 1993 the policy of all dosimetric services was to present the measured doses as such directly to the dose registration system. Now, several dosimetric services first apply a conversion factor, i.e. the dosemeter reading

taken outside the apron is divided by a factor of 5, before the result is reported to the dose registration system.

For fair comparison of the recorded doses to exposed employees it is necessary to harmonise the procedures. All parties concerned should conduct their activities according to certain rules they have agreed upon. In the present report a dosimetric protocol is given for the case of exposed employees wearing protective clothing.

1.7 Scope

Categories of professionals that are candidate for individual monitoring are shown in Table 1. In 2004 the National Institute for Public Health and the Environment (RIVM) reported a survey of the exposure of employees for the Ministry of SZW (Eleveld and Tanzi [21]). The survey is based on data from NDRIS, entered between 1993 and 2002 [22]. Recently an update of the statistical analyses of NDRIS data (1995-2004) became available (Van Dijk [23]).

In 2004 there were about 34,900 exposed employees with a personal dosemeter in The Netherlands. For 1950, 185 and 23 of them (5.6%, 0.5% and 0.1%) the recorded dose exceeded 1 mSv, 6 mSv and 20 mSv, respectively. A conversion factor may or may not have been applied, i.e. the measured dose may have been higher than the recorded dose. Amongst the professionals with a registered dose larger than 5 mSv, the majority belongs to the medical professions (172, of which 164 in diagnostic radiology). For 21 persons in this group a dose above 20 mSv was recorded. Two persons from other professional categories were registered in this highest dose category that year. They belong to the field of business applications (mobile non-destructive testing).
For comparison, the number of monitored professionals in The Netherlands in 2002 and those in another relatively small European country, Finland, in the same year (Rantanen [24]) is shown in Table 2. In Finland, twelve persons in a total of fifteen belonging to the highest dose category worked in health care. It should be kept in mind that also in Finland for medical X-ray examinations the personal dose is measured outside the lead apron.

Wearing protective clothing like a lead apron is useful only for certain types of radiation and energy ranges, i.e. where the attenuation effect of the thin layer of lead or lead equivalent material is significant. Therefore, not all professional groups will benefit from wearing an

Table 2 Numbers of radiological workers, in total and those with registered doses larger than a certain value in two smaller European countries (Finland [24] and The Netherlands [21]) in 2002.

Dose (mSv)	Finland						Netherlands	
	Total	%	Health care	%	Veterinary medicine	%	Total	%
	11,190	100	5,588	100	296	100	34,652	100
>0.5	1,900	17	548	10	29	10	2,754	8
> 1							1,497	4
> 5	344	3	89	1.6	3	1	218	0.6
>10	138	1	38	0.7	1	0.3		
>20	15	0.1	12	0.2	0	0		

apron. In hospitals and veterinarian practices aprons are worn most often (frequency 75% and 100%, respectively, whereas in other branches frequencies –if not zero– are 20-30% at maximum [20]).

In first instance the present report is aimed at radiology for medical purposes, in particular interventional radiology and cardiology, and at diagnostic radiology in veterinary medicine. In those cases, often the employee is exposed during prolonged times to 60-120 kVp X rays scattering off their nearby human or animal patient. $H_P(10)$ values measured outside protective clothing for staff members involved in heart catheterization are known to be amongst the highest encountered in medical practice due to their position close to the patient during extended periods of fluoroscopy and radiography. Measured personal dose values tending to the annual limit are not exceptional for those professionals [25]. Wearing protective clothing will reduce the effective dose considerably. It should be kept in mind, however, that in comparison to the total monitored population, i.e. about 35,000 persons with a personal dosemeter in The Netherlands, the group of exposed employees of concern in the present report is only very small (fewer than 200 or less than 0.6 per cent that both wears an apron and is relatively highly exposed).

2. Methods for determination of $H_P(10)$

2.1 Development of a system of operational quantities for radiation protection (external exposures)

With Report 39 [26] the International Commission on Radiation Units and Measurements (ICRU) has started a series of documents about methods for determining the dose equivalents resulting from exposure of the body to external sources of various types of ionising radiation. The first set of so-called operational dose equivalent quantities for monitoring of ionising radiation, necessary for radiation protection, is defined here. The report also discusses the desirable characteristics and capabilities of instruments for measuring the defined dose equivalents in practice.

Background information on the choice of the defined environmental and individual monitoring quantities (operational quantities, including the ambient dose equivalent (H*(d)), the directional dose equivalent (H'(d)), the individual dose equivalent penetrating ($H_P(d)$), and the individual dose equivalent superficial ($H_S(d)$) is provided in ICRU Report 43 [27]. Relationships between the quantities and the underlying calculated and experimental data for anthropomorphic phantoms and the ICRU sphere are discussed. A collection of physical data for photons, neutrons, beta rays and other electrons is presented, as well as information on the performance and calibration of existing instruments with respect to the defined monitoring quantities.

More details on design, calibration and use of instrumentation for measuring the dose equivalents in the case of external photon and electron radiation are presented in ICRU Report 47[1] [28]. Among the various instruments are ionisation chambers, proportional counters, Geiger-Müller counters, scintillation detectors, semiconductor detectors, photographic films, thermoluminescent dosemeters, thermally stimulated exoelectron emission detectors and photoluminescent detectors. Principles and practical methods for measurement of neutron radiation for radiological protection of employees in nuclear industry, civil aviation, medical, research and industrial applications are described in ICRU Report 66 [29].

Because of the often large uncertainties in quantities for use in radiation protection, sometimes approximations are unavoidable. A coherent system of dosimetric quantities and units is provided in ICRU Report 51 [30], with unambiguous definitions and clearly identified approximations that can be employed to demonstrate whether compliance with dose limitations exists.

[1] Report ICRU-47 (1992) and ICRP Publication 74 (1997) offer the same information.

2.1.1 Definition of $H_P(10)$

The operational quantity recommended for monitoring individual dose is the personal dose equivalent, $H_P(d)$ (previously: individual dose equivalent, penetrating).

$H_P(d)$ is the dose equivalent in soft tissue (ICRU: 76.2% oxygen, 11.1% carbon, 10.1% hydrogen, 2.6% nitrogen by mass; density: 1 g cm^{-3}) below a specified point on the body at a depth, d, where d=10 mm for strongly penetrating radiation and d=0.07 mm or 3 mm for weakly penetrating radiation, i.e. in the cases where the dose to the skin or the eye lenses, respectively, becomes the significant limitation. (Weakly penetrating usually applies to photons of energy below 15 keV and to beta radiation.)

2.1.2 A practical simplification for routine monitoring

Alberts and Dietze [31] proposed a practical simplification for routine monitoring of individual dose. When the objective is the surveillance of effective dose, use $H_P(10)$. When it is the surveillance of equivalent dose to the skin or the eye lenses, use $H_P(0.07)$.

2.2 Measurement and calibration

$H_P(d)$ can be measured with a detector that is worn at the surface of the body and covered with tissue-equivalent material of appropriate thickness. For calibration of the detector, it must be placed on an appropriate backscatter phantom. Calculated conversion coefficients relating air kerma (K_a) and $H_P(10)$ for a 30 cm x 30 cm x 15 cm slab phantom of ICRU tissue may be used (ICRU Report 47 [28]).

2.3 Dosemeters

Various types of dosemeter have been developed for use in different radiation environments. Most dosemeters have limited sensitivity with respect to radiation types (beta particles, gamma and X-ray photons, neutrons) and energy ranges. In 2004, the International Atomic Energy Agency (IAEA) has published an overview of types of personal dosemeter and their properties [32]. A year later, Bartlett and Tanner [33] discussed the suitability and adequacy of personal dosemeters and dosimetry systems as used for monitoring the workplace in the UK under various radiation exposure conditions.

These overviews may be helpful for employers to make a choice of personal dosemeters for their employees. Most current designs of whole body photon and electron dosemeters appear to have acceptable angle and energy dependencies to assess $H_P(10)$ and $H_P(0.07)$ for a large part of the entire particle/energy range of workplace exposures. However,

occasionally in-situ tests will be necessary to demonstrate actual suitability of a chosen dosemeter/dosimetry system.

The personal dosemeter (also called radiation badge) is usually worn on the trunk, outside of clothing, between neck and waist and facing forward. It may or may not be covered by protective clothing like an apron of lead-equivalent material. It is worn for a period of time during which it accumulates dose before being replaced. This wearing period depends on the magnitude of potential exposures and the type of dosemeter. Climatic conditions may also have an influence.

Passive detectors require suitable processing in a specialized laboratory to obtain the dose information. Examples are dosemeters based on photographic emulsions (film badges), thermoluminescence (TL) or radiophotoluminescence (RPL). After development of exposed sheet material the blackening (optical density), proportional to dose, can be measured with a densitometer. Thermo- or radiophotoluminescent crystals (phosphors) are treated with heat or UV radiation, respectively. This evokes emission of light, which can be quantified and is a measure of dose. Another method of quantification is nuclear track analysis (NTA). The number of radiation induced tracks per mm^2 counted on exposed material, or pits per mm^2 on a solid state detector determines the dose.

Active personal dosemeters (APDs; also called electronic personal dosemeters, EPDs) allow a direct read-out of the dose. They often have the disadvantage of an unsatisfactory energy response and most are not suited for beta fields. The advantage is that adjustable dose and dose rate alarms with audible warning can be set.

In radiology mostly TLD and film dosemeters are used for individual monitoring. In The Netherlands the most common personal dosemeter worn in medical environments is the TLD dosemeter (TLD badge). It usually provides information on both $H_P(10)$ and $H_P(0.07)$, owing to the presence of 2 (photon fields) or 3 (photon and electron fields) small lithiumfluoride detectors doped with various metals.

2.4 Intercomparisons of $H_P(10)$ measurements

From time to time it is tested whether personal dosemeters in use at dosimetric services and laboratories are indicating $H_P(10)$ within the accepted tolerances. This is done on a national basis (e.g. recently in The Netherlands: Bader *et al*. [34] and Sweden: Lund *et al*. [35]) or on a wider scale (e.g. Bordy *et al*. [36] or IAEA TecDoc-1126 [37], in which operational quantities, and an international comparison of both the dependence of dosemeter response

to energy and angular direction variations and their performance under realistic workplace field conditions are described). An earlier report by the EC (Radiation Protection 73 [38]) provides technical recommendations on dosemeters.
In the mentioned Dutch study acceptable agreement was found. The deviations between results of six dosimetric services fell within +10% and -20%, for mixed fields of 60 and 210 keV photons incident at various angles.

2.5 CONRAD Project: occupational exposure in radiology workplaces

CONRAD (a Coordinated Network for Radiation Dosimetry) is a current project (2005-2007) of Delft University of Technology, EURADOS and the University Sankt Gallen, sponsored by the EC within its 6th Framework Programme. One of the objectives of this project is to coordinate research into measurements and calculations for radiation protection at workplaces. It is carried out in a number of work packages (WP), in each of which groups of scientists from various laboratories in the EU member states participate.
Two WPs are of interest with regard to the present report, i.e. WP4, covering computational dosimetry, and WP7, dealing with the assessment of occupational exposures in interventional and diagnostic radiology workplaces. Amongst others these WPs set-up and will analyse a benchmark exercise, i.e. intercomparison of experimental and computational methods, regarding the characterization of the scattered radiation field in an interventional radiology procedure, dosemeter responses outside and under a lead-equivalent apron (so-called double dosimetry), and effective dose to the medical specialist performing the intervention. This will yield a better understanding of the reliability and uncertainty of computational techniques in radiation protection, in particular when applied to the determination of personal doses to cardiologists during cardiac catheterization. Next to double dosimetry WP7 is looking into the use of active personal dosemeters (APDs) and extremity dosimetry in interventional radiology, and intercomparisons with passive dosemeters with the aim to derive standards.
Evaluation of the results of the CONRAD project has not yet been completed. They could be taken into account to only limited extent in the present report.

3. Inventory of methods to modify dosemeter readings

3.1 Degree of Equivalence of $H_P(10)$ and E

For individual monitoring, normally a single personal dosemeter is used. According to regulations the maximum dose at any location of the body should be measured. If the radiation exposure is uniform, the best measurement position would be on the front of the trunk, between waist and neck (EDPG [6]). In general, dosemeter readings then will give acceptable indications of personal dose equivalent.

In workplaces, broad energy and direction distributions are usually present because of the direct and scattered components of the radiation. Significant spatial non-uniformity of the fields will add to non-uniform exposure of the body, which in turn makes it difficult to properly assess personal dose equivalent and effective dose by means of a personal dosemeter. In such cases it would be necessary to identify in advance the position of the highest dose and relocate the dosemeter accordingly. Another option is to use multiple dosemeters. The latter may be a solution to the problem of taking protective clothing into account. Different countries have different policies (e.g. Bartlett *et al*. [39]). For instance in Belgium (Belgian Bs [40]), and for certain circumstances also in Switzerland (Dosimetrieverordnung [19]), double dosimetry is applied, i.e. unshielded (outside the apron) and shielded (under the apron) dosemeter readings are used to establish the effective dose. An algorithm is used to derive effective dose from the dosemeter readings.

Even when a dosemeter yields a fair indication of personal dose equivalent, it may deviate considerably from the effective dose. A study by Chumak and Bakhanova [41] shows great dependence of the ratio $E/H_P(10)$ on photon energy, (anisotropic) irradiation geometry and dosemeter position. The ratio may be much larger than one.

In a study by Faulkner and Marshall [42] it was concluded that, with a single personal dosemeter, it is impossible to monitor effective dose accurately for all fluoroscopy conditions. In that study E was derived from TLD measurements in and on a Rando-Alderson phantom. The phantom was exposed to scattered radiation from 70 to 110 kVp X-ray beams as used in fluoroscopy procedures, and shielded by the usual types of apron. A personal dosemeter outside the apron overestimated E by a factor of 2 to 60. If shielded by the apron, the dosemeter underestimated E by a factor of seven.

Table 3 Application of conversion factors for photon dosimetry by dosimetric services in EU and associated countries.
(from Ambrosi *et al*. [43]), annotated by Eleveld and Tanzi [21])

Country	**Routinely application**	**Application in special circumstances**
Austria	No	No
Belgium	Depends on dosemeter type and dosimetric service	no information
Denmark	No	Yes, if dose > relevant dose limit. If $H_P(10)$>5 mSv, $H_P(3)$>15 mSv, $H_P(0.07)$>50 mSv then report to employer and National Health Council. If $H_P(10)$>10 mSv in 12 months the work procedures must be investigated.
Finland	No	Yes, if dose tends to the dose limit
France	No	If dose / dose limit > 0.1 an investigation is started.
Germany	No	If monthly dose / annual dose limit > 0.1.
Greece	No	No
Ireland	No	No
Italy	No	No
Luxemburg	No	If monthly dose > 1 mSv (0.1 annual dose) an investigation is started that may result in a correction.
Netherlands	Depends on dosimetric service	Upon request and after permission by authorities.
Portugal	No	No
Spain	No	If dose limit is exceeded, after investigation a correction may be applied; not obligatory.
Sweden	Calibration corrections of TLD readings	no information
Switzerland	No	If dose > annual dose limit
UK	Sometimes (for specific installations and if the information about the radiation field is sufficient), by the dosimetric service.	If dose > relevant dose limit the employer may request the dosimetric service to reassess the effective dose. The new value may be entered in an extra field in the national database upon request.

3.2 Conversions

As can be seen in Table 3 most EU and EU-associated countries do usually not apply conversion factors to measured personal dose values in routine applications, and when they do, it usually concerns neutron radiation. The Netherlands is an exception because two of its five approved dosimetric services apply a factor of 0.2 to be multiplied by the reading of the personal dosemeter located at an “outside-apron” position for photon irradiation.

In the USA the Nuclear Regulatory Commission (NRC) as the responsible agency does not permit dose weighting at present but it is recognized that straightforward individual monitoring may result in significant overestimation of the effective dose. Therefore, numerical relationships between monitoring data and effective dose are being reviewed for possible implementation at a later stage (Michel and Perle [44]).

In special circumstances, when measured personal dose tends to exceed or exceeds certain dose limits, some European countries (Table 3) allow, or even demand, reassessment of that dose, or rather of the effective dose. It is then investigated more thoroughly whether the dose limit really has been reached, almost reached or exceeded, by re-examining the actual exposure conditions.

In for instance the UK any corrective modification is entered into the national database beside the original value.

In The Netherlands it is possible to replace the original value in the national database by a modified value, but only after permission by the authorities. In such cases, the new and the old value are kept on record. Note that this is a procedure for *a posteriori* correction. *A priori* modification also occurs, as two approved dosimetric services supply dose values from “outside-apron” dosemeters, which they already have modified, as “original” to NDRIS.

3.2.1 Multiple dosemeters

Multiple personal dosemeters may be employed in complex radiation fields. They are especially useful when high levels of exposure and non-uniform exposure fields can be expected. The purpose of the additional dosemeter(s) is to gather more data for better estimation of the effective dose. This is still subject of ongoing studies, e.g. in the EC’s CONRAD project. Possible positions on the body to which a dosemeter might be attached are shown in Fig. 2.

When a protective apron is worn the application of double dosimetry may offer an improvement in comparison with a single personal dosemeter. The protective effect of the apron is better expressed by a pair of unshielded and shielded readings. Various dosemeter

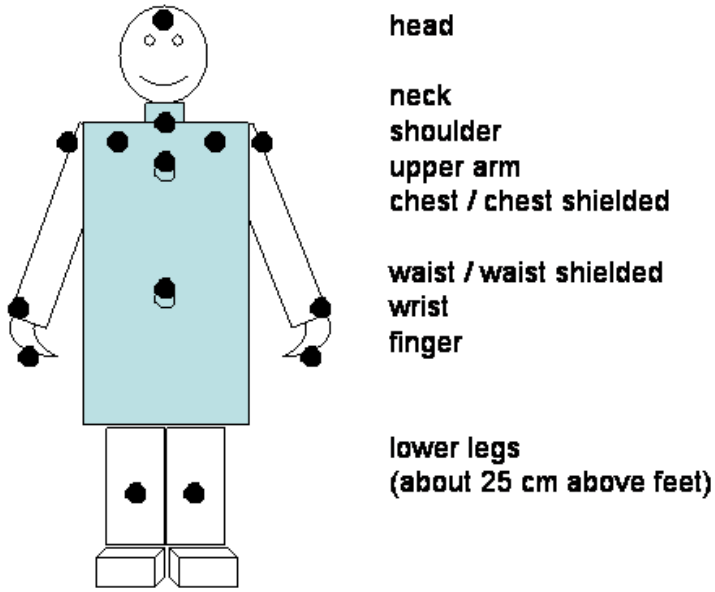

Fig. 2 Schematic view of positions on the body where dosemeters may be located. Chest and waist positions may be outside or under the apron. Preferred position in The Netherlands is chest unshielded or neck (unshielded). The professional's activities determine the actual position. Application of additional dosemeters depends on exposure conditions and (a priori estimated) level of radiation burden. Positions on the back are sometimes recommendable. Asymmetric positions should be towards the source of the radiation. (Based on Kicken [45].)

combinations occur: unshielded positions outside the apron at the neck, chest or waist with shielded positions under the apron at chest or waist.

In Belgium and Switzerland double dosimetry has already been made mandatory for certain radiological procedures (respectively, Belgian Bs [40] and Dosimetrieverordnung [19]). The Belgian rule is that if a professional in Belgium is likely to exceed three tenths of the annual dose limit (i.e. 0.3 x 20 = 6 mSv), double dosimetry should be applied.

Extremity dosimetry, with extra dosemeters at unshielded positions (head, arms, hands, legs) yields additional information about the dose to unprotected organs, e.g. skin and eye lenses. Usually, this information is not used to obtain an improved estimation of effective dose.

Effective dose contributions from body regions not protected by lead apron and thyroid collar (if worn) for operators and assistants in vascular radiology have been investigated in a study by Kicken *et al*. [46]. It was concluded that the dose to the head, the unprotected thyroid, upper arms and hands, and lower legs contributed significantly. Relative contributions by these tissues of about 70% and 90% were estimated, respectively, without and with the thyroid collar. The calculated reduction in effective dose by the thyroid collar was calculated as a factor of two.

3.2.2 Conversion algorithms

Algorithms have been constructed to obtain information about the effective dose from personal dosemeter reading(s) in case protective clothing is worn. Such algorithms are based on the analysis of several studies in the literature. They assume a basic form with one or two parameters.

Algorithms for single dosimetry

The algorithm to derive effective dose from the reading of a single personal dosemeter comprises a simple conversion factor. The unshielded dosemeter reading should be divided by a factor F_1:

$$E = H_U / F_1 \tag{3}$$

and the shielded dosemeter reading should be multiplied by a factor M_1:

$$E = H_S \cdot M_1 \tag{4}$$

Values for parameters F_1 and M_1 as found in literature are shown in Table 4.

Algorithm for double dosimetry

The algorithm to derive effective dose from the readings of two personal dosemeters is a combination of eq. (3) and eq. (4):

$$E = H_U / F_2 + H_S \cdot M_2 \tag{5}$$

Values for parameters F_2 and M_2 as found in the literature, and very recently summarized by Järvinen *et al*. [47], are shown in Table 4.

3.2.3 More about the parameter values

Huyskens *et al*. [58] and Franken *et al*. [48] made extensive studies of the exposure of medical staff during several radiological procedures. With computer simulation they calculated organ and effective doses and shielded and unshielded dosemeter responses for

Table 4 Parameter values for the conversion algorithms.

Single dosimetry, outside apron (eq. (3))			
Reference	wearing position	F_1	Remarks
NCRP-122, 1995 [16]	neck	21	based on medical fluoroscopy procedures [42]; may lead to overestimation of E up to a factor of 3.4
Kicken *et al*., 1995 [46]	neck	10 20 (with TC)	0.5 mm Pb apron, interventional radiology
Franken *et al*., 2002 [48]	mid-front, neck or chest	5	conservative estimate, actually ≥5
Tsapaki *et al*., 2004 [49]	neck	15 30 (withTC)	interventional cardiology
CONRAD Project, 2006 *(see Table 7)*	mid-front, high on chest	20 (with TC)	0.25 mm Pb apron

Single dosimetry, under apron (eq. (4))			
Reference	wearing position	M_1	Remarks
NCRP-122, 1995 [16]	waist	6.7	based on medical fluoroscopy procedures [42]; may lead to overestimation of E up to a factor of 11.2

Double dosimetry (eq. (5))					
Reference	wearing position		F_2	M_2	Remarks
	unshielded	shielded			
Wambersie *et al*. 1993 [50]	neck or shoulders	chest	10	1	-
Swiss Ordinance on Personal Dosimetry, Art. 14 [19]	-	-	10 20 (with TC) 1	1 1 1	rather than E, eq. (5) calculates $H_P(10)$ calculates $H_P(10)$ calculates $H_P(0.07)$
Rosenstein-Webster, 1994 [51] and NCRP-122, 1995 [16]	neck	waist	40	0.5	-
Niklason *et al*., 1994 [52]	neck	waist	15 50 (with TC)	0.93 0.98	at neck: $H_P(0.07)$ measurement, at waist: $H_P(10)$ measurement
McEwan, 2000 [53]	collar	trunk	20	0.71	-
Franken *et al*., 2002 [48]	mid-front neck or chest	abdomen	10 30 (with TC)	1 1	- -
Sherbini et al., 2002 [54]	neck	waist	15	1	-
Von Bötticher et al., 2003 [55]; Lachmund, 2005 [56]	neck	thorax	13.5 60 (with TC)	0.65 0.65	- -
Clerinx et al., 2007 [57]	neck	thorax	13.3	1.64	10% margin for underestimation

TC: thvroid collar

Table 5 Conversion factors for personal dosimetry with a single dosemeter. (Franken *et al*. [48])

average value of factor $\mathbf{F_1}$ (eq. 3) for good (left) or bad (right) fit of the apron
frontal apron without thyroid collar; 80% AP + 20% LAT irradiation
dosemeter outside apron, mid-front at chest or collar level

tube voltage	apron thickness (mm Pb)							
(kVp)	0.15		0.25		0.35		0.5	
50	13	9.1	15	10	16	10	16	10
70	9.7	7.1	13	8.5	14	8.9	15	9.1
90	5.9	4.7	8.5	6.1	10	6.9	12	7.4
110	4.3	3.6	6.3	4.7	8.0	5.5	9.9	6.2
125	3.9	3.3	5.6	4.3	7.2	5.1	9.1	5.9
	for a photon spectrum with more filtration (3.5 mm Al + 0.1 mm Cu)							
90	4.9	4.0	7.3	5.3	9.2	6.1	11	6.7
110	3.7	3.2	5.5	4.2	7.1	5.0	9.1	5.7
125	3.4	3.0	5.0	3.9	6.5	4.6	8.4	5.4

average value of factor $\mathbf{F_1}$ (eq. 3) for good (left) or bad (right) fit of the apron
wrap-around apron + thyroid collar; 60%AP + 30% LAT + 10% PA irradiation
dosemeter outside apron, mid-front at chest or collar level

tube voltage	apron thickness (mm Pb)							
(kVp)	0.15		0.25		0.35		0.5	
50	33	27	63	43	71	46	72	47
70	16	14	34	27	47	34	56	38
90	6.9	6.6	13	12	21	17	31	24
110	4.5	4.3	7.8	7.3	12	11	19	16
125	4.0	3.8	6.7	6.3	10	9.2	16	14
	for a photon spectrum with more filtration (3.5 mm Al + 0.1 mm Cu)							
90	5.3	5.1	10	9.2	16	14	26	20
110	3.8	3.7	6.5	6.1	10.0	9.1	16	14
125	3.4	3.3	5.6	5.3	8.5	7.8	14	12

average value of factor $\mathbf{M_2}$ (eq. 4) for average fit of the apron
wrap-around apron; 60%AP + 30% LAT + 10% PA irradiation
dosemeter under the apron at chest or waist level

tube voltage	apron thickness (mm Pb)			
(kVp)	0.15	0.25	0.35	0.5
50				
70	1.2	2.2	5	11
90	1	1.5	2.2	3.5
110	1	1.2	1.7	2.2
125				

Table 6 Conversion factors for personal dosimetry with a single dosemeter. Small patient, narrow beam. (Schultz *et al*. [59])

diagnostic heart catheterization procedure patient: baby boy; 5 cm x 7 cm field at skin entrance; PA; 59 kVp, 3 mm Al				
factor $\mathbf{F_1}$ (eq. 3); dosemeter outside apron, on right shoulder (away from X-ray source!)				
	frontal apron		wrap-around apron	
	0.25 mm Pb	0.5 mmPb	0.25 mm Pb	0.5 mm Pb
broad beam of scattered radiation, unidirectional 45° oblique from front-left	12	12	15	26
realistic field of scatter from patient	21	25	48	76
factor $\mathbf{M_1}$ (eq. 4); ; dosemeter under apron, on right shoulder (away from X-ray source!)				
	frontal apron		wrap-around apron	
	0.25 mm Pb	0.5 mmPb	0.25 mm Pb	0.5 mm Pb
broad beam of scattered radiation, unidirectional 45° oblique from front-left	5	6	4	5
realistic field of scatter from patient	7	6	3	2

broad beams of scattered radiation (50–125 kVp X-ray sources). The orientation of the beam (monodirectional) with respect to the radiologist and the typical relative duration of the exposures were taken into account. They examined the protection efficiency of several types and thickness of protective apron, with and without a thyroid collar, and derived conversion factors relating dosemeter reading(s) to effective dose as a function of tube voltage (kVp) and apron thickness (mm Pb). Resulting conversion factors for single dosimetry are summarized in Table 5.

Schultz *et al*. [59] used Monte Carlo (MC) simulation techniques to calculate the dose to a cardiologist performing a catheterization procedure for diagnosis of paediatric congenital heart disease. The influence of the model (frontal, wrap-around) and thickness (0.25 mm Pb, 0.5 mm Pb) of the apron was investigated. Also the field characteristics were changed, i.e. a broad unidirectional beam of scattered radiation quality was compared to exposure to actual

Table 7 Conversion factors for personal dosimetry with a single dosemeter.

Wrap-around apron + thyroid collar of same Pb-equivalent thickness.
Adult patient, broader beam. Realistic field of scatter.
(CONRAD project, see section 2.5)

interventional cardiology procedure
patient: adult male; 24 cm x 24 cm field at skin entrance; 80 kVp, 3.5 mm Al + 0.3 mm Cu

factor $\mathbf{F_1}$ (eq. 3);

	PA view		LAT view	
dosemeter outside apron	0.25 mm Pb	0.5 mmPb	0.25 mm Pb	0.5 mm Pb
at chest position	17.5	37	25	-
at waist position	5	11	20	-

Influence of dosemeter position.

Dosemeter outside apron, at a central position on the trunk or shifted 10 cm horizontally to left or right (towards or away from the source, respectively). Vertical position from chest to waist, starting 5 cm below shoulder line going down with 15 cm steps. Wrap-around apron + thyroid collar, 0.25 mm Pb.

	factor $\mathbf{F_1}$ (eq. 3);				
PA view	chest →→	→→→→→→	→→→→→→	→→→→→→	→→ waist
Left	26.0	27.2	19.6	8.2	25.7
Central	18.6	17.0	11.6	3.3	14.6
Right	12.1	8.9	5.9	1.6	7.8
LAT view	chest →→	→→→→→→	→→→→→→	→→→→→→	→→ waist
Left	26.4	35.3	41.8	33.2	34.3
Central	19.7	24.2	24.4	17.7	17.3
Right	12.2	14.2	11.9	7.4	7.8
	factor $\mathbf{M_1}$ (eq. 4);				
PA view	chest →→	→→→→→→	→→→→→→	→→→→→→	→→ waist
Left	0.5	0.5	0.4	1.8	0.4
Central	1.8	1.5	4.5	10.4	2.6
Right	7.8	5.4	22.3	17.5	52.2
LAT view	chest →→	→→→→→→	→→→→→→	→→→→→→	→→ waist
Left	0.6	0.8	0.4	0.5	0.4
Central	3.7	4.1	1.7	2.4	2.6
Right	29.5	10.4	8.6	12.2	26.5

scatter from the patient. Resulting conversion factors for single dosimetry are summarized in Table 6.
A similar investigation (Schultz *et al.* [60]) has been conducted recently within the framework of the CONRAD project (section 2.5). Here, an adult patient in a cardiac interventional procedure is considered. Exposure conditions are based on those recently observed in a number of Belgian hospitals (Struelens [61]). A rather large field is used. The dosemeter position, outside or under the apron, is varied on the trunk of the cardiologist. The resulting conversion factors are given in Table 7.

Results of entrance dose measurements for the operator in interventional radiology as a function of the height from the floor have been derived for 20 procedures (Kicken [62]). Although the entrance dose levels varied per procedure, all procedures showed similar patterns. Up to about 80 cm from the floor the doses at different heights were relative constant, then gradually decreased with increasing height to a factor of 5–10 lower level at 180 cm.

These studies show that there is considerable variation in the conversion factors, depending on the exposure conditions, the protective measures and the wearing position of the dosemeter.

Reviewing systematic measurements in studies by e.g. Mateya *et al*. [63] and Kicken *et al*. [46, 64], Padovani *et al*. [65] concluded that the official USA recommendations of NCRP-122 [16] lead to overestimation of effective dose by a factor of up to 3-4 for single dosimetry. More serious underestimation occurs by applying the recommended Rosenstein-Webster algorithm [51] to double dosimetry. The algorithm for double dosimetry by Niklason *et al*. [52] seems to be in better agreement with literature data.
Based on this review Tsapaki *et al*. [49] adopted a conversion factor different from the NCRP-122 recommendation for application of single dosimetry in an interventional cardiology procedure. The Tsapaki algorithm, and for double dosimetry the Niklason algorithm, are still considered the most appropriate for this branch of radiology (e.g., Maeder *et al*. [66]). In case of single dosimetry the dosemeter then can best be worn outside the apron in frontal position at the neck, corresponding with a conversion factor (eq. (3)) F_1=15 or F_1=30, without or with a thyroid collar, respectively. The results of the CONRAD study presented in Table 7 indicate a conversion factor F_1=20 (with collar) if the dosemeter is worn high on the chest, corroborating earlier results by Kicken *et al.* [64]. Concerning double dosimetry, any concensus about the most suitable calculation algorithm is not firm yet. Without further investigation it is uncertain

whether an optimum algorithm exists that covers all interventional radiology procedures (Järvinen *et al*. [47]).

3.3 Exposure conditions in The Netherlands

The vast majority of professionals that wear lead aprons is involved in health care (93%). In particular, they work in hospitals (74%) and in veterinary medicine (19%) (De Jong *et al.* [20]). Aprons are not worn much in the other branches (Table 1). Within the category of health care workers with lead aprons, the two groups with relatively high potential exposure are the specialists in interventional radiology and interventional cardiology, and those who perform diagnostic radiology procedures in veterinary medicine (NDRIS data, [22, 23]). The exposure conditions for these two groups are explored below.

3.3.1 Interventional radiology / cardiology

Procedures

The most important types of treatment performed by means of interventional radiology and cardiology (DBC registration [67]) are listed in Table 8. The number of therapeutic X-ray interventions performed in 2002 amounts to about 1 per 1000 inhabitants. While information on dose to the medical staff is not given in the database (RIVM [68]), it will be (much) lower than the patient dose, which is rated at 5 mSv on average per procedure.

Equipment

X-ray equipment used for fluoroscopy and angiography is also used in interventional radiology. The maximum tube voltage is 140 kVp (Brugmans [69]). Often a lower setting is used, i.e. down to 50 kVp but mostly between 70 kVp and 90 kVp. For example, in sixty nine procedures of paediatric heart catheterizations performed in three children's hospitals the technical parameters were 57–90 kVp, 2–18 mAs for fluoroscopy and for cine imaging (at 12.5–25 frames s^{-1}) 54–89 kVp, 300–770 mAs, with 3 mm Al equivalent filtration in both modes. The rather large spread is due to differences in patient size and complexity of the procedures (ASD closure, RF ablation, balloon dilatation and patent ductus arteriosus occlusion) (Spoelstra [70]).

In a series of thirty cerebral neurointerventional procedures in adults and children the settings were 71–110 kVp, 1–6 mA and 75–85 kVp, 133–192 mA during fluoroscopy and cine imaging (0.3 frames s^{-1}), respectively, with 3.3 mm Al equivalent filtration (Spoelstra [70]).

Table 8 The most important types of radiological or cardiological intervention [67].

- PTA (stenosis and occlusion)
- placement of stent or stent graft
- embolisation
- local administration of pharmaceuticals
- neurointerventions
- fibrinolysis
- mechanical thrombectomy
- drainage
- placement of vena cava filter
- (tumour) ablation
- removal of stone (kidney, bladder) or corpus alienum

In a study by Kicken [62] tube voltage measurements were performed in about 1060 interventional procedures. To derive typical values, tube voltages during short periods of time were weighted with the dose area product (DAP) during that time interval. DAP weighted voltages varied between 55 and 105 kV per examination, with an average value of 78 kV.

In CT guided interventions the tube voltage usually amounts to 120 kVp.
General and special dosimetric, image quality and ergonomic considerations regarding the optimal use of radiology equipment for interventional radiology can be found in e.g. Zoetelief and Faulkner [71].

Geometric configuration
Due to the nature of interventional radiology it cannot be avoided that medical staff is standing close to the couch and the unattenuated X-ray beam during longer periods of time, thus being exposed to scattered radiation. Although this also holds for assisting staff, like anaesthetist, nurse or assistant radiologist, and a sometimes present radiographer or (echo)cardiographer, it is especially true for the interventional radiologist or cardiologist, who is closest to the patient. In the example of paediatric heart catheterizations mentioned in the previous section, the mean catheterization time was 86 (range 15–220) minutes, with 21 (2–79) minutes fluoroscopy time and 28 (2–165) seconds cine imaging [70].
Regarding the position and orientation of the interventional radiologist or cardiologist with respect to the patient, it is rather common that the former stands to the right of the latter, who

An X-ray unit in undercouch position as used for interventional radiology. Note the presence of a lead-acryllic screen and a lead curtain hanging from the patient table. (photograph: courtesy of LUMC Radiology Department.)

lies in supine position on the couch. When present, the anaesthetist and the radio-/cardiographer are standing at the head and at the feet of the patient, respectively. The nurse or assistant radiologist stands at the same side as the radiologist or cardiologist. In this configuration, during a series of 30 cerebral neurointerventional embolisation procedures the average occupational dose to the anaesthetist, assistant radiologist and radiographer were, respectively, about 0.5, 0.3 and 0.1 times that to the interventional radiologist (reading of outside-apron personal dosemeter) (Spoelstra [70]).

Protective measures

An apron of lead equivalent material, of either frontal or wrap-around type, is always worn and often a thyroid collar. The thickness of the apron varies from 0.25 to 0.5 mm Pb. The value is chosen by the local expert on radiological protection, who balances exposure conditions and comfort. The thyroid collar has a thickness of 0.5 mm Pb.

A facial mask and/or goggles are not common but are sometimes used in interventional cardiology. More frequently ceiling suspended lead-acrylic glass screens are applied instead, and lead curtains fixed to the patient table in case of an undercouch tube.

Gloves are also worn rarely.

Wearing position of dosemeter(s)

Usually a single personal dosemeter is worn outside the apron, fixed to hang from the thyroid collar, thus at high mid-frontal position on the trunk (De Jong and Van Dijk, [20]).

3.3.2 Veterinary medicine

Procedures / general remarks

Neither The Netherlands nor the EU authorities have issued special instructions on the use of ionising radiation and individual monitoring for veterinary practices. In the Netherlands the general instructions specified in the Bs [2] apply. Employees should leave the room, withdraw behind appropriate shielding or be equipped with adequate protective clothing before the X-ray unit starts operating.

In the USA radiation safety with regard to the protection of individuals who may be exposed to radiation emitted by X-ray equipment in the practice of veterinary medicine is the subject of NCRP Report 148 [72]. Amongst others, attention is given to the use of radiographic, fluoroscopic and therapeutic equipment, taking into account specific factors pertinent to radiation protection in veterinary medicine. X-ray machines are widely used but in general at a low workload, hence the occupational exposure of personnel is, on average, low. However, the necessity of (technical assistants) restraining animals and holding film cassettes require

proper execution of recommended operational procedures, including individual monitoring and application of lead aprons and thyroid collars. Various measures aimed at reduction of animal patient dose yield a proportional reduction of occupational exposure.

State authorities, e.g. the Department of Health Services of the State of California, professional groups and other bodies also have published radiation safety instructions [73, 74, 75]. These are based on the four pillars of veterinary radiation safety, i.e. reducing exposure time, keeping distance from the radiation source, shielding and common sense [76].

The latest insights into this category of application of ionising radiation and radiation protection issues are currently being put down into the Australian Code of Practice for Radiation Protection in Veterinary Science (2005) [77]. Amongst others it is proposed to prescribe that all persons who cannot stay behind protective screens should wear an apron of at least 0.25 mm Pb and not less than 0.5 mm Pb when energies above 100 kVp are used. However, no information is given about the wearing position of a personal dosemeter.

Equipment

X-ray equipment is used at technical parameter settings that are similar to interventional radiology, i.e. tube voltage varies between 50 and 140 kVp. It is estimated, however, that only about 5-10% of the X-ray equipment can be operated at tube voltages of 100 kVp or higher (De Jong *et al*. [78]).

Geometric configuration

Special devices have been designed for fixation of an animal during irradiation. Still, it cannot always be avoided that staff must remain in the X-ray room during the examination to keep the animal relaxed and in a steady position.

Protective measures

Lead aprons are always worn, usually of the frontal type with 0.5 mm Pb equivalent or of the mantle type with overlapping flaps offering 2x 0.35 mm Pb equivalent protection. A thyroid collar (0.5 mm Pb equivalence) is also worn routinely. So are lead gloves that protect the hands and lower arms. The face (eyes) is never protected.

Wearing position of dosemeter(s)

A single personal dosemeter is worn, either in a central position on the trunk (mostly at collar level) or fixed to the sleeve of one of the upper arms.

3.3.3 Protective equipment

The International Atomic Energy Agency has published international basic safety standards (BSS) for radiation protection [79] and a separate guide concerning occupational exposure [80]. The agency also published about the methodology for an individual monitoring programme, covering the dosimetric quantities, specifications and tests of personal dosemeters, dose registration and quality assurance aspects [81]. Regarding personal protective equipment (PPE) suitable for the professional groups considered here, lead equivalent gowns, aprons and thyroid protectors are mentioned [82]. They are made of a fabric, e.g. rubber or vinyl based, which contains lead. Manufacturers are developing new materials without lead, which are less heavy, thus more comfortable to wear. Their protective capacity is still under discussion. To reduce weight, conventional aprons may be open at the back if the wearer is always facing the radiation source or may contain less lead. Otherwise a so-called wrap-around or mantle type of apron is used. The BSS prescribes that if the X-ray machine operates up to 100 kVp the minimum lead equivalent thickness must be 0.25 mm. If it operates above 100 kVp the minimum thickness increases to 0.35 mm. Care should be taken not to wrinkle the garments as creases might lead to loss of protective effectiveness. Gauntlets or heavy gloves are often difficult to use, especially in medical practices and therefore are required only in appropriate cases. Other protective devices are goggles, screens and lead curtains. According to the BSS, ceiling suspended protective screens and protective lead curtains mounted on the patient table are indispensable in fluoroscopy and interventional radiology.

For individual monitoring the BSS recommends to wear the dosemeter (film badge, TLD or electronic device) at waist level under the apron for effective dose assessment. In case of high exposure, like in interventional radiology an additional dosemeter might be worn outside the apron at collar level. This dosemeter will yield an indication of the doses to the thyroid and eye lenses. Also, eq. (5) can be used, with F_2=2 and M_2=0.025, to calculate effective dose. When wearing a thyroid collar, an additional reduction in E by a factor of 2 can be applied.

The recommendations laid down in the BSS are not quite in line with recent literature. That the BSS of 1996 is growing obsolete is recognized by the IAEA, hence an update is planned in the near future.

For interventional radiology and cardiology in particular, protective devices like a thyroid collar, spectacles and a lead-acrylic face mask may reduce the doses to radiosensitive organs in head and neck (eyes, brain and sinuses, thyroid and oesophagus). Dose reduction

from marginal up to 97 per cent with respect to the unprotected situation can be achieved, depending on the type and specifications of the device (Marshall *et al*. [83]).

4. Alternatives for the protocol

In many countries the application of lead aprons is prescribed by legislation for those activities in which these protective garments can significantly attenuate the energy of the radiation and offers effective radiation protection. There is less international consensus about the place of the personal dosemeter: outside or under the protective clothing. The EU Member States tend to the recommendation to wear the dosemeter on the outside. The main reason is to have an opportunity to evaluate, if necessary, also the exposure of any not covered part of employee's body, for instance the eyes. However, the rules vary from country to country. In some EU Member States it is recommended to wear the dosemeter outside the apron and to perform a recalculation when the dose exceeds a certain level. Other countries request to place the dosemeter under the apron for easier direct comparison of doses (the effect of the protection is included in the measurement). For the time being this is also the point of view of the IAEA.

In this chapter the possible choices regarding the "lead apron protocol" are discussed. Arguments against or in favour of an option will be given. A requirement is the broad applicability of the protocol, e.g. the procedures must be simple, cheap, not irritating, but above all robust (i.e. safe with regard to radiation protection), without sacrificing dosimetric correctness too much.
Although differences in costs of options will not be considered here, the costs aspect should not be forgotten. It will comprise initial costs for changing the infrastructure of a procedure, e.g. adapting the NDRIS database, and repetitive costs, e.g. because of adding components to a measurement cycle.

Alternatives exist with respect to:

1. Protective clothing, i.e. type and thickness of lead apron and thyroid collar.
2. Other personal protective equipment, e.g. lead gloves, spectacles, facial mask.
3. Dosemeters,
   - single or multiple?
   - wearing position.
4. Other measures of dose reduction.
5. Conversion factor to be applied to the dosemeter reading(s).
6. The groups of occupationally exposed persons for which the code of practice applies.
7. Organizational aspects.

4.1 Protective clothing

The radiation equipment and exposure conditions used in interventional radiology (IR) and veterinary medicine (VM) are such that lead equivalent aprons and thyroid collars offer effective protection. A lead apron may reduce effective dose by a factor of 5–20 or more. A thyroid collar may add an additional factor of 2. Therefore, in The Netherlands both types of protective clothing are very frequently worn in IR and VM.

4.1.1 Lead apron

Both in IR and VM frontal and wrap-around (mantle) type aprons are used. The choice may depend on the department's tradition and budget for purchasing equipment, but it should certainly depend on the orientation of the exposed employee with respect to the radiation source. In IR the thickness may vary from 0.15 to 0.5 mm Pb, depending on the judgment of the responsible expert (local radiation protection officer (RPO) or general advisor (RPA)), who considers the employee's comfort in good balance with safety. In VM the thicker apron is used (0.5 mm Pb), i.e. in the case of a wrap-around apron the thickness actually is 0.35 mm Pb but at the front the two flaps overlap, resulting in the total of 0.7 mm Pb.
From Table 5 it can be deduced that taking care of a good fit and shielding from all directions can be more important than merely increasing the lead thickness.
Disadvantages of the lead or lead containing composite aprons are the physical strain (5–15 kg), some hindrance of the freedom of movement and other discomfort (e.g. lack of ventilation). Aprons of completely lead-free materials are appearing on the market. They contain less heavy protective elements like oxides of tin, antimony, tungsten and bismuth. Therefore, they may be more comfortable to wear. For equal Pb equivalence, however, they may offer less protection, e.g. due to induction of significantly more secondary (fluorescent) radiation. This should be carefully investigated before bringing into use (Eder *et al.* [84], Finnerty *et al.* [85]). As manufacturers of lead-free aprons are reluctant to reveal the exact elemental composition of their materials, accurate calculations of the protective effectiveness of such aprons cannot be made. Henceforth conversion factors appropriate for those aprons are not available yet. Therefore, the use of lead-free aprons is not advised at the moment.
An apron management system will be necessary, e.g. to check regularly that the apron is not creased, wrinkled or leaking radiation. In larger hospitals such a management system is usually available. Article 10.1.C of the Bs [2] requires regular verification of efficacy and correct use of protection equipment and safety procedures, at a minimum frequency of once a year.

Responsibility for proper use of this provision may be put at the exposed employee and the RPO/RPA.

4.1.2 Thyroid collar

The thyroid collar is always worn in combination with the lead apron. The thickness is usually 0.5 mm Pb. It protects the thyroid and the oesophagus. Effective dose can be reduced by up to a factor of two. It should be noted here that proper use of a thyroid collar is paramount. If the collar is only “loosely” attached, the thyroid may still be partly or completely exposed. The protective effect then is significantly reduced.
Disadvantages of the thyroid collar are discomfort and hygienic problems. To overcome the latter disadvantage every eligible professional should be issued a personal collar.
The thyroid collar may be convenient as a location to fix the personal dosemeter to.
Responsibility for proper use of this provision may be put at the exposed employee and the RPO/RPA.

4.2 Other personal protective equipment

4.2.1 Facial mask or spectacles

A lead-acrylic facial mask offers some additional protection to the head and neck. Spectacles –that also should offer lateral shielding, like goggles– protect the eye lenses. They are seldom worn in IR, only occasionally by interventional cardiologists. In VM they are not used at all. If worn, this provision is always combined with lead apron and thyroid collar.
Disadvantages are discomfort, misting up of the glasses, putting pressure on the bridge of the nose and causing headache. Spectacle lenses should be adapted to the eyesight of the professional.
Responsibility for proper use of this provision may be put at the exposed employee and the RPO/RPA.

4.2.2 Gloves

Thin gloves covering the hands are used very infrequently in IR, e.g. when contact with the direct exit beam cannot be avoided. In VM gloves (0.5 mm Pb thickness) of the gauntlet type, i.e. covering hands and lower arms, are always worn when positioning an animal. Gloves are always combined with a lead apron.

Gloves offer some additional protection of the skin and possibly, to lesser extent, of bone and bone marrow.
A great disadvantage of gloves is that they may seriously hamper accurate locomotion of hands and fingers, as required for handling surgical instruments. Also, a gloved hand moving into the primary beam may be counterproductive in so-called AEC-systems as it causes extra scattered radiation coming towards the exposed employee.
Responsibility for proper use of this provision may be put at the exposed employee and the RPO/RPA.

4.3 Dosemeters

While a high degree of discipline may be expected of the exposed employee, responsibility for the implementation of rules about wearing the dosemeter may primarily be put at the RPO/RPA. In general the latter has best knowledge of the local exposure conditions and should be able to interpret the corresponding dosemeter readings correctly.

4.3.1 The number of dosemeters

According to Dutch law participation in the individual monitoring programme with at least one dosemeter is mandatory when exposed employees may receive more than 1 mSv effective dose per year. This is the case in IR. Also in VM high doses are not excluded, although actually the measured doses often appear to remain below the threshold. At present, members of both professional groups wear a personal dosemeter.
In IR much variation in exposure conditions occurs. Here, for better insight into the radiation burden of the exposed professional, application of multiple dosemeters certainly can be advantageous. Departments sometimes experiment with an additional dosemeter (EPD), e.g. when exposure may be high like in CT guided reconstruction of the vertebrae, or in interventional cardiology. An EPD yields a direct reading of the dose and also allows setting an alarm level. Continuous application of two dosemeters in Dutch hospitals is very rare.
Only for special circumstances in IR more than two dosemeters are applied. In particular it may be useful when extremities are exposed.

Using multiple dosemeters has advantages from a dosimetric point of view, and may lead to better radiation protection. Obviously it yields more information about the exposure. It enables doing simple cross-checks to detect abnormalities, for instance by looking at the ratio of two dosemeter readings (one outside, one under the apron).

In principle, double dosimetry should enable more accurate estimation of effective dose than single dosimetry in complex radiation fields. Tested algorithms exist to derive effective dose from the dosemeter reading(s), both for single and for double dosimetry (Tsapaki and Niklason, respectively, see Table 4). Not everybody, however, is fully satisfied with them. In particular the parameter values in the double dosimetry algorithms are subject of on-going discussion.

In a recent multi-centre study [47] it was concluded that the difference between the accuracy of double and single dosimetry algorithms was not significant. This immediately was weakened by the limited number of exposure conditions that could be considered. Therefore, generalisation of the conclusion is not really possible. On the other hand, neither does it justify the immediate abandonment of traditional single dosimetry. Schultz et al. [60], for example, showed that effective dose to the interventional cardiologist could be assessed with a single dosemeter placed at a central position high on the chest. But here too, the exposure conditions were limited as only two (typical) views were considered.

Double dosimetry requires increased attention because users can easily make mistakes by mixing up the dosemeters. (Note that application of the Niklason algorithm for double dosimetry requires a $H_P(0.07)$ dosemeter outside the apron at the neck and a $H_P(10)$ dosemeter under the apron at the waist. Those dosemeters should be clearly marked.) Although probably not difficult to overcome, extra discipline, organizational measures and a good labelling system will be necessary, implying a higher administrative (and financial) burden. Changing dosemeter badges is, at present, centrally organized in only about 55% of the practices (De Jong [20]), so in many cases responsibility for good practice is in the hands of the exposed employee. This should be transferred to the RPO/RPA.

For routinely performed procedures there seems to be no urgent reason to prescribe double dosimetry. Double dosimetry may be better, in principle, but there is not yet enough knowledge about properly converting observed data to effective dose to justify the corresponding organizational changes to be necessarily introduced in clinical practice. Single dosimetry, as presently established in almost all radiology departments, still seems to suffice for achieving reasonable estimates of effective dose.

4.3.2 Wearing position of the dosemeter(s)

A questionnaire returned by a representative sample from the Dutch occupationally exposed employees with a personal dosemeter revealed that chest (53%), collar (18%), waist (15%)

and sleeve (upper arm/shoulder, 11%) are the usual wearing positions (De Jong [20]). The same source reports that 80% of the professionals with an apron wears the dosemeter – single dosimetry is standard in The Netherlands– outside the apron. No specification was given of the distribution of the dosemeter positions in relation to wearing an apron. In IR and VM, however, the dosemeter is worn outside the apron.

Wearing a single dosemeter outside the apron results in relatively high measured values in a range in which the instrumental accuracy is pretty good. If worn under the apron it is very well possible that a reading cannot be obtained because of the attenuated radiation intensity staying below the instrumental detection level. Attenuation factors in clinical practice have been derived to amount up to 100 [46]. Also, it is easier to calculate accurate conversion factors for this unshielded situation compared to when the dosemeter is under the apron. Furthermore, a measurement outside the apron also gives an indication of the exposure of the unshielded organs, e.g. of importance for the eye lenses, which otherwise can never be retrieved.

Still, some countries of the EU and a few international organisations on radiological protection prescribe wearing the dosemeter under the apron.

The thyroid collar is a convenient position in IR, putting the dosemeter high and centrally on the trunk. In VM this position is also chosen often, although high on the upper arm (left or right) may occur. Such latter position may lead to wrong dose indications if the dosemeter is on the side that is turned away from the source. (Besides, in general dosemeters show at least some directional sensitivity differences.)

A central position high on the chest seems preferable as it results in the least sensitivity to the beam direction (e.g. Table 7). For practical reasons it is unwise to suggest varying the dosemeter position during or in between procedures to account for different beam directions. Consistently wearing the dosemeter at a less optimal position is better than introducing irregularities and errors by trying to place the dosemeter constantly at the best location.

When opting for double dosimetry the often preferred conversion algorithm by Niklason implies a $H_P(0.07)$ dosemeter outside the apron at the neck and a $H_P(10)$ dosemeter under the apron at the waist, presumably mid-front.

4.4 Other measures for dose reduction

While less obvious in VM, in the case of IR a few other measures for dose reduction can be taken. For instance, ceiling suspended lead glass screens and lead equivalent curtains can be used. The former may protect the eyes of the interventional radiologist/cardiologist in a less aggravating way than facial masks and/or spectacles. Larger screens also offer protection to other organs than only the eyes. A possible disadvantage may be that such a screen –usually 0.5 mm Pb equivalent– may shield the dosemeter, although perhaps not continuously, decreasing the dose estimate in a way that is difficult to interpret.

Lead curtains can be attached to the edge of the couch, thus offering shielding from an undercouch tube. In IR they are applied often, but they also occur in VM. The lead equivalent thickness is 2–2.5 mm. Curtains are prone to getting dirty, thereby forming a hygienic risk. They also get in the way when views are used that require large angulations or rotation.

Some recently invented protective measures are for instance the wearing of lead caps by interventionalists (Kuon *et al.* [85]) or covering the patient with a radio-opaque blanket (King *et al.* [86]). Another proposed innovation is to put the radiological operator in a mobile booth, the Cathpax radiation protection cabin [87]. Behind 2 mm Pb-equivalent walls including transparent leaded plastic the operator has freedom of movement and does not have to put on any protective garments. As these are all still unusual solutions they will not be considered here.

Although screens and curtains are often applied, certainly in IR, in the determination of the conversion factor for the lead apron dosimetry problem their protective effect is ignored. Proper quantification of the influence on the radiation field is rather complex. Both the dosemeter reading and the effective dose to the exposed employee will be affected, but probably not to the same extent. Until more reliable information becomes available, however, proportionality of the changes is assumed. The factor for converting the dosemeter reading then remains constant. Because of this uncertainty in such a situation, choosing a modest value for the conversion factor avoids arriving at a dose value that possibly would underestimate the effective dose.

4.5 Conversion factor to be applied to the dosemeter reading(s)

To reach a desired high level of quality in radiological protection, it is necessary to produce dose estimates that are as close to their true value as can be reasonably achieved. By applying a conversion factor to the reading of a personal dosemeter, it is possible to obtain a more accurate value for the effective dose. The purpose of harmonisation is to treat equal

cases everywhere in the same way, thus allowing easy comparison of dose values from different institutes. In the present case the question is, what conversion factor to apply, and when. This is especially important when the level of exposure is high and protective clothing is worn. It will prevent falsely identifying groups of employees as (too) highly exposed just on the basis of a dosemeter reading, without taking into account the effect of the protective measures.

Useful conversion factors are available only for aprons and apron-thyroid collar combinations. A further restriction is that the apron material must contain lead, as the new lead-free aprons have not yet been evaluated in this respect. Influence of other protective measures is not accounted for. This is mainly due to the problem of complexity, i.e. difficulties in adequately generalising the complex exposure conditions, rather than that it is considered of secondary importance. It means, however, that the true dose (effective dose) still is unknown after application of the proposed protocol. Only a much better estimate is obtained.

When opting for double dosimetry the currently optimal conversion algorithm by Niklason implies a $H_P(0.07)$ dosemeter (H_U) outside the apron at the neck and a $H_P(10)$ dosemeter (H_S) under the apron at the waist, presumably mid-front. The conversion algorithm

$$E = H_U / F_2 + H_S \cdot M_2 \qquad (5)$$

should be used, where F_2=15 or 50 and M_2=0.93 or 0.98, respectively, without or with the collar being worn.

When the choice would be single dosimetry with the dosemeter (H_U) worn on the apron at a high central position (neck or high on the chest, e.g. attached to the thyroid collar) the conversion

$$E = H_U / F_1 \qquad (3)$$

must be made, where F_1 = 5 independent of whether a thyroid collar is or is not worn and independent of the tube voltage. This value of F_1 is a conservative estimate and should be applied when the apron has a thickness of 0.25 mm Pb equivalent or more. For thinner aprons no conversion is applied as in those cases the overestimation of the dose would not be too large.

The advantage is that it is a simple procedure. The factor of 5 is already applied by a few approved dosimetric services in The Netherlands. The numerical value of 5 is based on

studies in which apron thickness and fit were varied, as well as the tube voltage applied (Franken et al. [48]).
A drawback is that only a few average exposure geometries could be considered. However, also from other studies (Table 4) the factor of 5 seems to be a conservative correction, i.e. it is the lowest value found in the series of test conditions –assuming good fit and minimum thickness of 0.25 mm Pb– and it will usually be (much) higher for actual conditions. Therefore, application of this factor can be considered safe, for it still will overestimate effective dose.

Table 4 suggests that larger conversion factors might be applied for better approximation of effective dose. On the other hand, use of protective screens and curtains in interventional radiology/cardiology is not uncommon nowadays. This introduces additional uncertainty as its effect has not yet been properly accounted for. It could be that the overestimation of effective dose after application of the factor of 5 is not as large as believed.
Anyway, the obtained reduction in dose obtained after application of the factor of 5 may not be the most accurate one, but it will be sufficient to keep highly exposed employees away from the annual dose limit. A condition is that the dosemeter is worn outside the apron in a central position high on the chest or at neck level.

A refinement may be considered in the sense that the conversion factor could be varied depending on the thickness of the apron and the tube voltage applied. This is shown in Table 9, together with the conditions for which applying the correction factor would be allowed. With these values, based on the literature data presented in Chapter 3 (Table 5, in particular), the modifications would still be rather conservative. In view of the large uncertainties, rounding the values to multiples of 5 would be permissible. Although it may perhaps give the wrong impression that additional lead thickness or a thyroid collar sometimes would offer no extra protection, it has the advantage of dealing with fewer different values of the conversion factor.

It might be considered to modify only dosemeter readings of so-called A-employees (effective dose more than 6 mSv per year, Art. 79 of the Bs [2]). Especially in VM the majority of professionals will never be exposed that high. In their case modification would turn low dose readings in even lower “real” dose values, which might lead to the wrong opinion that radiation exposure is no more than a triviality.

Table 9 Conversion factors as a function of apron thickness and tube voltage.

The reading of the dosemeter should be divided by the factor below.
Conditions:

- Conventional aprons (i.e. protective material contains lead).
- No modification will be applied for aprons of less than 0.15 mm Pb equivalent.
- The dosemeter is worn outside the apron in a central position high on the chest or on the collar.
- The apron should fit well.
- The appropriate type of apron (frontal or wrap-around) will be chosen as to shield the exposed employee from radiation coming from the predominant direction(s) at the workplace.
- In case of a wrap-around apron with overlapping flaps the single flap thickness should be selected rather than double flap thickness, unless absolutely sure that the overlap is predominantly directed to the radiation source.
- Thyroid collar is used approriately and has at least the same thickness in mm Pb equivalent as the apron, else use conversion factor for no collar.
- Tube voltage should stay within the indicated ranges during the time and/or the procedures during which the dosemeter is worn.

	tube voltage (kVp)		
apron thickness mm Pb equiv.	< 80	80 – 120 **NO** thyroid collar	> 120 - 140
0.15	5	4	3
0.25	7	6	5
0.35	9	7	6
0.5	11	9	8

	tube voltage (kVp)		
apron thickness mm Pb equiv.	< 80	80 – 120 **WITH** thyroid collar	> 120 - 140
0.15	5	4	3
0.25	10	7	6
0.35	16	10	8
0.5	26	16	14

On the other hand, distinguishing between these categories may introduce artificial dose differences that will disturb the general analyses of the distribution of doses to exposed employees.

Responsibility for application of the proper conversion factor should be with the employer, i.e. the one responsible for ordering the dosemeters to be worn. This may be delegated to the responsible expert (RPO/RPA) or, in smaller hospitals or practices, a radiological protection

committee or medical physicist who is familiar with the local exposure conditions and the work methods of the exposed employees. Conferring with the Labour Inspectorate (“Arbeidsinspectie” SZW) or a similar competent authority, this licensed person or body should state that the exposed employees comply with the protocol and that, therefore, the chosen conversion factor is to be applied. Both original dose ($H_P(10)$ and modified dose (effective dose estimate) then can be recorded in NDRIS.

4.6 The groups of professionals for which the code of practice applies

As mentioned before, two groups of professionals have been identified who wear lead aprons and may be highly exposed according to analyses of the NDRIS data. The groups consist of specialists in interventional radiology and interventional cardiology, and those who work in veterinary diagnostic radiology.

There is no doubt that the persons of the first group should be included in the code of practice. Doses outside the apron as indicated by their personal dosemeter are in general relatively high, and, when based on these measurements without applying a correction, these professionals run a serious risk of exceeding their annual dose limit.

Possibly, in the near future, gastero-enterologists will form another group of medical specialists eligible for application of the code of practice. The dose to those who perform growing numbers of radiological procedures is also considerable. It cannot be excluded that at some time they will exceed the annual dose limit, based on personal dose measured outside the apron.

For the exposed employees in veterinary diagnostic radiology the situation is quite different. Although, according to the NDRIS data, this group is present in the higher dose ranges, in general these employees stay well below the annual dose limit. In fact, the dose to the individual exposed employee is most often low to very low, even when measured with the personal dosemeter outside the apron. Application of a conversion factor would most frequently bring the estimated effective dose below 1 mSv per year, which means that wearing a dosemeter would in fact not be mandatory. For reasons of safety, not wearing the personal dosemeter at all should not be advised and people should not be tempted to trivialise the dose they receive.

It seems appropriate to exclude the veterinarians as a relevant group of exposed employees for the code of practice. The code of practice would then be restricted to the group of exposed employees in interventional radiology and cardiology. Those persons would really benefit from the more realistic estimation of effective dose by the application of a modification to the dosemeter reading.

4.7 Organizational aspects

For purpose of quality assurance, certain checks will be necessary. There should be no mistakes in applying a conversion factor to a dosemeter reading. One must be sure that the dosemeter has been used in conditions for which the code of practice is valid. In this respect the ADSs might issue dosemeters with clear special marks to indicate their exclusive use for individual monitoring with a conversion factor. On the other hand the ordinary dosemeter identification system may suffice if the administrative link to its special use is easily recognisable. The sytem of record keeping should be well maintained anyway.

Also the communication routes should be clear. Mutual two-sided communication between several parties will make that any error will be noticed. The parties concerned are the user, the local radiation safety expert (RPO/RPA), the ADS, the NDRIS administrator, and the competent authority (Labour Inspectorate). The most likely roles –though others can be thought of– are that the latter supervises, checks and approves, based on requests by the local expert at the user's facility and reports from the NDRIS administration. Knowing the workplace conditions of the user, the local expert selects the conversion factor to be applied, obtains approval from the Inspectorate and informs the ADS. The ADS determines the dosemeter reading. It communicates the actual dosemeter reading and its modified value to the NDRIS administrator. It also reports the values back to the local expert, who in turn informs the user. At a later stage the same information will once more reach the local expert through the periodical reports received from the NDRIS administrator. The local expert thus can double-check the data stored, and so can the Inspectorate.

An infrastructure and detailed "screenplays" should be designed and implemented to enable flawlessly such lines of communication.

Another question is whether the local expert should determine the conversion factor and request approval for each measurement cycle of the dosemeter. Alternatively, this could be done once and be maintained until the workplace conditions change after, perhaps, many measurement cycles. The second option means less administrative burden. It may be advisable though, for reason of awareness, to have the local expert declare periodically, for instance after the update of the risk-assessment procedure (at least once in three years), that the exposure conditions remained unchanged.

5. Recommended code of practice

Validity of the code of practice

A number of conditions determine the validity of the code of practice. If not all conditions are met, the code of practice shall not be applied to determine modified readings of the personal dosemeter for registration in NDRIS.

Target groups

In first instance, the code of practice concerns exposed employees in the professional group of interventional radiology and cardiology who are routinely performing interventional procedures under well-known exposure conditions. Before applying the protocol to new or experimental procedures, the responsible radiation safety expert must carefully analyse the differences and similarities of the exposure conditions. Furthermore, consent of the competent authority (e.g. Labour Inspectorate) must be obtained. The same holds for any intention to apply the code of practice to other groups of exposed employees who wear protective clothing.

Exposed employee and local expert

Both the exposed employee and the local expert have to follow the procedures laid down in this code of practice.

The local expert is the appointed person in charge of the department's radiation safety, i.e. the responsible radiation protection advisor (RPA) or the responsible radiation protection officer (RPO). The RPA/RPO is adequately qualified with respect to radiation protection (level 4A or better in The Netherlands).

Exposure conditions: tube voltage range

The code of practice concerns employees who are exposed to scattered radiation from X-ray sources with tube voltages up to 140 kVp.

Exposure conditions: protective aprons

The exposed employee wears an undamaged and unwrinkled apron that fits well. The code of practice concerns conventional aprons, not the lead-free types, i.e. the protective material may be a composite but must contain lead. The reason for this is that appropriate conversion factors for lead-free aprons are not available at present, as explained before in section 4.1.1.

In accordance with the tasks that the employee performs, the RPA/RPO chooses an apron of suitable type and thickness. The following marked paragraphs may serve as guidance:

- The choice of apron type must be proper for the circumstances at the workplace. When the radiation will predominantly come from frontal direction (frontal quadrants) and the employee needs not turn around very much, a frontal type apron will do. A wrap-around (gown, mantle) type of apron is necessary when scattered radiation is likely to come from various directions. The latter is often the case in interventional radiology/cardiology as the X-ray tube rotates around the patient and operators and assistants move around a lot.
- In case of paediatric radiology (tube voltage up to 80 kV) the minimum apron thickness is 0.15 mm lead equivalent.
- In case of general interventional radiology, when operating conventional X-ray equipment at tube voltage up to 120 kVp, the minimum apron thickness is 0.25 mm lead equivalent.
- In case of CT-guided interventions (tube voltage above 100 kVp) the minimum apron thickness is 0.35 mm lead equivalent.
- With a wrap-around apron the thickness of for instance 0.5 mm may be achieved with two overlapping flaps of 0.25 mm each. A wrap-around apron of 0.25 mm lead equivalent thus can be used instead of a 0.5 mm lead equivalent frontal apron. A condition is that it is predominantly this frontal part of the apron that faces the field of radiation.

Thyroid collar?

After conferring with the RPA/RPO, the exposed employee may or may not wear a thyroid collar. A thyroid collar is worn only in combination with a protective apron. When a thyroid collar is worn, it must have a lead equivalent thickness of at least the same value as the apron.

Wearing position of dosemeter

For routine procedures the exposed employee shall wear a single personal dosemeter at a central position high on the chest, outside the apron. Preferably the dosemeter is attached to the thyroid collar, if present.

Care should be taken that a **lead-acrylic screen** –if used– does not shield the dosemeter while leaving substantial parts of the exposed employee unshielded. The latter situation is not covered by this code of practice.

Table 10 Conversion factors (CF) without or with a thyroid collar as a function of apron thickness*.

If all conditions of the code of practice are fulfilled the reading of the dosemeter is to be divided by the factor below.

Restriction: Use of the factor for 0.15 mm Pb equivalent apron thickness is prohibited **UNLESS** the tube voltage never exceeds 80 kVp (as may occur for e.g. paediatric interventions).

apron thickness mm Pb equiv.		NO thyroid collar		WITH thyroid collar
0.15		*5*		*5*
0.25		**5**		**5**
0.35		**5**		**10**
0.5		**10**		**15**

*Note that in principle more protection is offered when the apron is thicker, the thyroid collar is present and the tube voltage is lower. Equal numbers in different cases are due to rounded figures.
This table should be used to select a CF for a given protection level, NOT to select a protection level based on an appealing CF.

Permission of the competent authority

Only if the work is performed in accordance with the code of practice, the competent authority (in the Netherlands: Labour Inspectorate, “Arbeidsinspectie SZW”) grants permission (implicitly) to apply a conversion factor to the dosemeter reading. The RPA/RPO informs the competent authority once about his intention to use dose modification according to the Code of Practice.

Periodic checks on exposure conditions

Together with the exposed employee, the RPA/RPO examines whether the conditions of the protocol are fulfilled and they file a declaration on this situation. They check periodically – once a year– whether the exposure conditions have changed. In between such checks it is left to common sense to notice and evaluate any deviations from the protocol. The checks form part of the mandatory risk-assessment procedure (Bs, Art. 10 [2]).

Selection of conversion factor

The RPA/RPO selects the appropriate conversion factor (CF) from Table 10, depending on the employee’s apron thickness and the presence or absence of a thyroid collar.

If the value of a parameter (apron thickness, presence or absence of a thyroid collar) varies during the measurement cycle (i.e., period that the dosemeter is worn before being read), the corresponding lowest correction factor shall be applied.
If the thickness of a lead apron deviates from the values mentioned in Table 10, the conversion factor for the next lower thickness present is to be selected. No conversion factor is applied if the apron thickness is less than 0.15 mm lead equivalent.
The RPA/RPO may select another value for the CF than listed in Table 10 if he can prove that it yields a more accurate estimate of the effective dose. The proof must be well documented and be satisfactory to the Labour Inspectorate.

Record keeping

The RPA/RPO shall keep records concerning the results of the checks and the choices of protective matters and CF in the radiation hygiene file of the exposed employee.

Tracking dosemeters

The RPA/RPO shall carefully keep track of the personal dosemeters for which he desires application of the modification procedure to the measured dose. He sees to it, that those dosemeters are correctly used.

Liaison to the competent authority

The RPA/RPO is the liaison with the competent authority (Labour Inspectorate).
The competent authority performs its usual auditing tasks as a supervising body. It may verify correct application of the Code of Practice by demanding access to the documentation kept at the facility.

Liaison to the approved dosimetric service

The liaison with the approved dosimetric service is, as usual, the RPA/RPO.
At the end of the measurement cycle the RPA/RPO sends the personal dosemeter to the ADS and requests application of the “lead apron” procedure. To that purpose he provides the value of the conversion factor.

Approved dosimetric service

The approved dosimetric service determines the dose measured with the personal dosemeter ($H_P(10)$). The ADS also calculates the modified dose ($H_{P,NCS}$) as the ratio of the measured value and the conversion factor (CF):

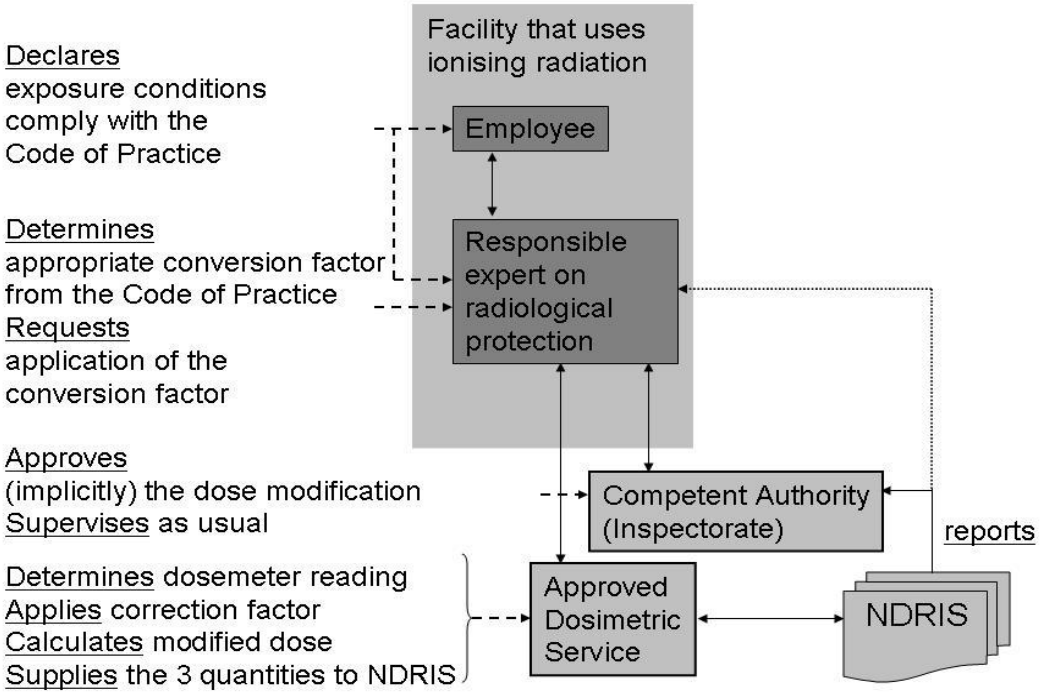

Fig. 3 Schematic view of responsibilities of parties involved in executing the code of practice. Otherwise, existing procedures apply, e.g. with respect to reporting activities.

$$H_{P,NCS} = H_P(10) / CF \quad (6)$$

The ADS reports the values of the three quantities to the administrator of the dose registry (NDRIS). The ADS also passes them on to the RPA/RPO.

The ADS bears full responsibility for the correctness of the measured dose value, but not for the appropriateness of the CF. The latter is the responsibility of the RPA/RPO.

NDRIS

The NDRIS administrator enters the values of the measured dose, $H_P(10)$, and the modified dose, $H_{P,NCS}$, in the database. In due time, in the usual manner, he reports the data to the competent authority and, upon request only, to the RPA/RPO.

Overview of responsibilities

Fig. 3 schematically shows an overview of responsibilities when working according to the code of practice. In principle, normal procedures are followed, just like for measurement cycles of other personal dosemeters. The exceptions are

- Both the exposed employee and his RPA/RPO declare and check regularly that the work is performed according to the conditions specified in the code of practice.
- The RPA/RPO determines the appropriate conversion factor from the code of practice (Table 10) and requests the application of this factor.
- The ADS determines the original and modified dosemeter readings. The ADS forwards the values of the quantities for registration in NDRIS and informs the RPA/RPO.
- The RPA/RPO keeps the records of all matters concerning the procedure, suitable for examination by the Labour Inspectorate.

Aanbevolen protocol

Geldigheid

Een aantal voorwaarden bepaalt de geldigheid van het “dosimetrie-loodschortprotocol”. Als niet aan de in het protocol gestelde voorwaarden wordt voldaan, mag dit protocol niet worden toegepast om de uitlezing van de persoonsdosismeter te wijzigen voor registratie in NDRIS.

Doelgroep

Het protocol is in eerste instantie opgesteld voor blootgestelde werknemers in het vakgebied van de interventieradiologie en –cardiologie, voor zover zij de gebruikelijke, routinematige werkzaamheden verrichten. Dit zijn de huidige interventieprocedures, waarvoor de blootstellingscondities goed bekend zijn. Alvorens kan worden overgegaan tot toepassing van het protocol bij het invoeren van een nieuwe of experimentele werkwijze, of eventueel in andere vakgebieden waar loodschorten gedragen worden, moeten overeenkomsten en verschillen in de blootstellingscondities zorgvuldig worden geanalyseerd. Waarna nog goedkeuring van de Arbeidsinspectie moet worden verkregen.

Blootgestelde werknemer en locale deskundige

Zowel de blootgestelde werknemer als zijn/haar locale deskundige draagt verantwoording voor het naleven van het protocol.

Onder locale deskundige (algemeen coördinerend stralingsdeskundige) wordt verstaan de door de werkgever aangewezen persoon, bij de stralingsbeschermingseenheid of elke andere eenheid, die binnen de faciliteit of afdeling toezicht houdt op en verantwoordelijkheid draagt voor de stralingsbescherming. De locale deskundige heeft minimaal opleidingsniveau 4A op het gebied van stralingsbescherming. De locale deskundige wordt hieronder verder aangeduid met de afkorting RPA (van het Engelse Radiation Protection Advisor).

Blootstellingscondities: buisspanning

Het protocol betreft werknemers die worden blootgesteld aan verstrooide straling afkomstig van röntgenapparaten met een buisspanning van ten hoogste 140 kVp.

Blootstellingscondities: loodschort

De blootgestelde werknemer draagt een onbeschadigd loodschort, van goede maat en pasvorm. Het moet een conventioneel loodschort zijn, dat wil zeggen, het beschermende materiaal mag een composiet zijn, maar moet lood bevatten. Het protocol geldt niet voor de

nieuwe lichtgewicht schorten van loodvrij beschermingsmateriaal. De reden hiervoor is, dat er momenteel geen geschikte conversiefactoren bekend zijn voor loodvrij materiaal, zoals eerder aangegeven in sectie 4.1.1.

Naar aanleiding van de werkzaamheden die de blootgestelde werknemer verricht, kiest de RPA het geschikte type loodschort en de loodschortdikte. Als hulpmiddel gelden hierbij de volgende richtlijnen.

- De keuze van het loodschorttype moet zijn afgestemd op de werkomgeving. Als de straling voornamelijk uit voorwaartse richting komt, en de werknemer niet veel draait, volstaat een frontaal loodschort. Een loodschort van het manteltype.is nodig wanneer de strooistraling uit verschillende richtingen kan komen, zoals bij rotatie van de röntgenbuis rondom de patiënt en bij mogelijke draaibewegingen van de drager. Dit komt beide veel voor bij interventieradiologie/-cardiologie.
- Bij kinderradiologie (buisspanning tot 80 kVp) is de loodschortdikte minimaal 0.15 mm loodequivalent.
- Bij algemene interventieradiologie (interventies met een röntgenstatief, buisspanning tot 120 kVp) is de loodschortdikte minimaal 0.25 mm loodequivalent.
- Bij CT-geleide interventies (buisspanning hoger dan 100 kVp) is de loodschortdikte minimaal 0.35 mm loodequivalent.
- Met een loodschort van het manteltype kan de dikte van bijvoorbeeld 0.5 mm worden bereikt door twee flappen van 0.25 mm over elkaar heen te slaan. In dat geval kan een manteltype van 0.25 mm looddikte dus worden gebruikt in plaats van een frontaal loodschort van 0.5 mm. Men moet dan wel zeker weten dat het stralingsveld hoofdzakelijk op dit overlappende frontale deel van het loodschort gericht is.

Schildklierkraag?

De blootgestelde werknemer kan, in overleg met de RPA, een schildklierkraag dragen. Een schildklierkraag wordt altijd in combinatie met een loodschort gedragen. Als een schildklierkraag wordt gedragen, moet de dikte in mm loodequivalent minstens gelijk zijn aan die van het loodschort.

Draagpositie dosismeter

Bij het uitvoeren van routinematige procedures gebruikt de blootgestelde werknemer een persoonsdosismeter, gedragen op een centraal punt hoog op de borst en buiten het loodschort. Bij voorkeur wordt de dosismeter bevestigd aan de schildklierkraag, als die wordt gedragen.

Tabel 10 Conversiefactor (CF) zonder of met schildklierkraag als functie van loodschortdikte*.

Als wordt voldaan aan alle voorwaarden van het protocol moet de uitlezing van de persoonsdosismeter worden gedeeld door de onderstaande factor.

Beperking: Het gebruik van de conversiefactor voor loodschortdikte van 0.15 mm Pb equivalent is **ALLEEN** toegestaan als de ingestelde buisspanning nooit meer bedraagt dan 80 kVp (bijvoorbeeld interventies bij kinderradiologie).

schortdikte mm Pb equiv.		GEEN schildklierkraag		WEL schildklierkraag
0.15		*5*		*5*
0.25		**5**		**5**
0.35		**5**		**10**
0.5		**10**		**15**

*Merk op dat de bescherming in principe groter is bij een dikker loodschort, bij het dragen van een schildklierkraag en bij lagere buisspanning. Dat in verschillende gevallen een gelijke correctiefactor wordt vermeld is het gevolg van afronding.
Deze tabel moet worden gebruikt om bij gegeven beschermingsmiddelen een bijpassende CF te zoeken, NIET om bij een ”aantrekkelijke” CF de beschermingsmiddelen te kiezen.

Als er een **scherm van loodglas** (loodacryl) wordt gebruikt, mag deze de dosismeter niet afschermen terwijl substantiële delen van de blootgestelde werknemer er niet door worden afgeschermd. In deze laatste situatie geldt dit protocol niet.

Goedkeuring Arbeidsinspectie

Alleen indien bij de werkuitvoering wordt voldaan aan alle eisen die het protocol stelt, staat de Arbeidsinspectie het (impliciet) toe om de uitlezing van de persoonsdosismeter te modificeren. De RPA stelt de Arbeidsinspectie eenmalig op de hoogte van zijn voornemen om dosismodificatie volgens het protocol toe te passen.

Periodieke controle op blootstellingscondities

De RPA toetst samen met de blootgestelde werknemer of aan de voorwaarden van het protocol wordt voldaan en zij leggen dat schriftelijk vast. Zij controleren periodiek –eens per jaar– of de blootstellingscondities zijn veranderd. Tussentijds wordt op basis van gezond verstand gesignaleerd of mogelijk deviaties van het protocol optreden die nadere evaluatie

behoeven. De controles maken onderdeel uit van de verplichte risico-analyse (Bs, Art. 10 [2]).

Keuze van conversiefactor

De RPA kiest de conversiefactor (CF) uit de in Tabel 10 vermelde waarden, afhankelijk van de gebruikte loodschortdikte en het al dan niet dragen van een schildklierkraag.

Als de waarde van een parameter (loodschortdikte, aan-/afwezigheid van een schildklierkraag) varieert gedurende de periode dat de persoonsdosismeter wordt gedragen (de meetcyclus), moet de overeenkomstige laagste conversiefactor worden toegepast.

Als de loodschortdikte afwijkt van de in Tabel 10 genoemde waarden, wordt de conversiefactor voor de eerstvolgende wel voorkomende lagere loodschortdikte gebruikt. Voor loodschortdiktes onder de 0.15 mm loodequivalent wordt geen conversie toegepast.

De RPA mag een CF-waarde kiezen die afwijkt van Tabel 10, mits hij kan bewijzen dat hij daarmee een nauwkeuriger schatting van de effectieve dosis verkrijgt. Dit bewijs moet goed gedocumenteerd zijn en goedkeuring wegdragen van de Arbeidsinspectie.

De RPA legt het resultaat van de toetsen en keuzes vast in het stralingshygiënisch dossier van de blootgestelde werknemer.

Bijhouden administratie

De RPA houdt administratie bij van de persoonsdosismeters die hij in aanmerking wil laten komen voor wijziging bij uitlezing. Hij ziet toe op het juiste gebruik ervan.

Contactpersoon voor Arbeidsinspectie

De RPA onderhoudt contact met de Arbeidsinspectie.

De Arbeidsinspectie voert als toezichthouder de gebruikelijke controles op de gang van zaken uit. De Arbeidsinspectie kan de correcte toepassing van het protocol altijd verifiëren door informatie (documentatie) op te vragen bij de RPA.

Contactpersoon voor erkende dosimetriedienst

De RPA onderhoudt contact met de erkende dosimetriedienst.

Aan het eind van de meetcyclus stuurt de locale deskundige de persoonsdosimeter naar de dosimetriedienst met het verzoek de “loodschortprocedure” toe te passen. Hij stuurt hiertoe de te gebruiken conversiefactor mee.

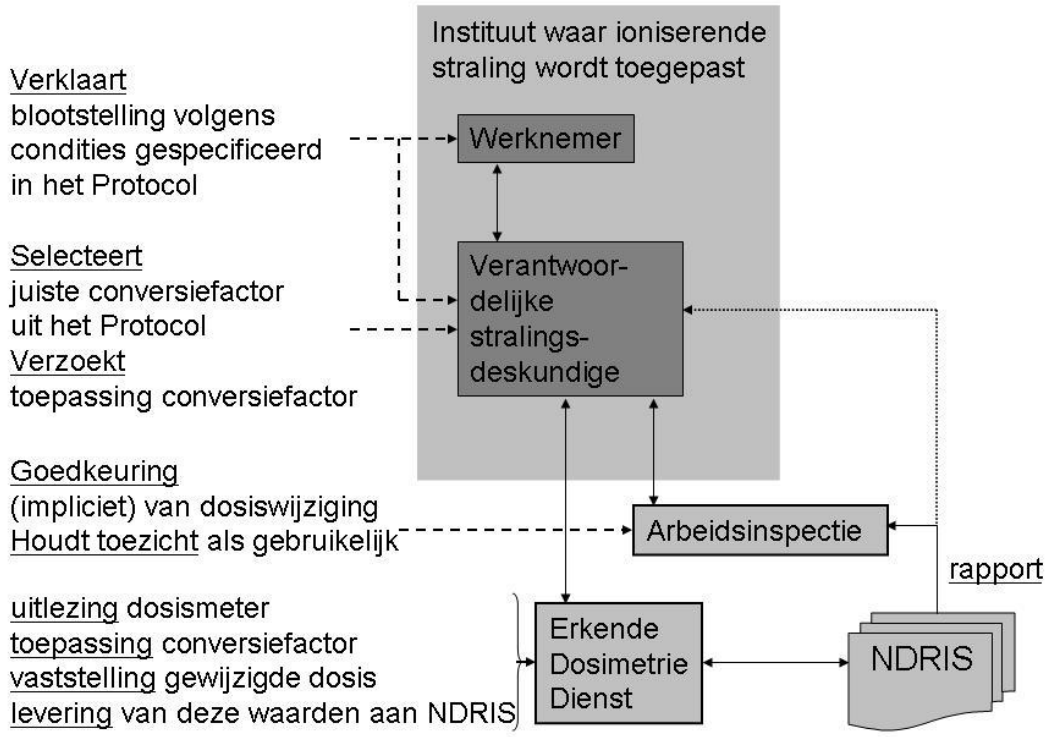

Fig. 3 Schematisch overzicht van verantwoordelijkheden van betrokkenen bij het uitvoeren van het loodschortprotocol, voor elke meetperiode met de persoonsdosismeter. Verder worden de gebruikelijke werkwijzen gevolgd, onder andere voor rapportage.

Erkende dosimetriedienst

De erkende dosimetriedienst leest de persoonsdosismeter uit en bepaalt de gemodificeerde dosis ($H_{P,NCS}$) door de gemeten waarde ($H_P(10)$) te delen door de conversiefactor (CF):

$$H_{P,NCS} = H_P(10) / CF \qquad (6)$$

De dosimetriedienst stuurt de waarde van de drie grootheden door naar de beheerder van NDRIS, en meldt ze ook terug naar de RPA.

De dosimetriedienst is verantwoordelijk voor de juistheid van de gemeten dosis ($H_P(10)$), maar niet voor de juistheid van de conversiefactor. De verantwoordelijke voor de laatste is de RPA.

NDRIS

De beheerder van NDRIS registreert zowel de gemodificeerde dosis ($H_{P,NCS}$) als de oorspronkelijk gemeten dosis ($H_P(10)$). Op de gebruikelijke wijze rapporteert hij op gezette tijden aan de Arbeidsinspectie en, alleen op verzoek, aan de RPA.

Overzicht van verantwoordelijkheden

Fig. 3 toont in schema een overzicht van verantwoordelijkheden van diverse betrokkenen bij het werken volgens het protocol. In beginsel wordt alles op de gebruikelijke manier gedaan, net zoals voor elke andere persoonsdosismeter per meetperiode. De uitzonderingen zijn

- Zowel de blootgestelde werknemer als de RPA verklaren, en controleren regelmatig, dat de werkzaamheden zijn verricht volgens de condities die in het protocol worden genoemd.
- De RPA bepaalt de juiste conversiefactor uit Tabel 10 van het protocol en verzoekt aan de erkende dosimetriedienst om toepassing ervan.
- De erkende dosimetriedienst leest de persoonsdosismeter uit en modificeert de dosis met behulp van de conversiefactor. De gemeten en gemodificeerde dosiswaarden, evenals de correctiefactor, worden opgestuurd naar NDRIS en teruggemeld aan de RPA.
- De RPA houdt documentatie bij over alle zaken aangaande het loodschortprotocol, zodanig dat de Arbeidsinspectie haar taken als toezichthouder kan vervullen.

Acknowledgement

The authors wish to thank all persons who, after reading the draft version of this report, have offered comments, made suggestions or raised questions. Their contributions were helpful for further discussion within the subcommittee, and valuable for the finalisation of this report.

References

[1] EC. Council Directive 96/29/Euratom of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation. Off. J. Eur. Commun. 39 (L-159), 1996.
[EC. Richtlijn 96/29/Euratom van de Raad van 13 mei 1996 tot vaststelling van de basisnormen voor de bescherming van de gezondheid der bevolking en der werkers tegen de aan ioniserende straling verbonden gevaren. Publicatieblad van de Europese Gemeenschappen L-159, 29 juni 1996.]

[2] Bs. Besluit van 16 juli 2001, houdende vaststelling van het Besluit stralingsbescherming. Staatsblad van het Koninkrijk der Nederlanden, Nr 397, 2001.
(available in pdf format from http://docs.szw.nl/pdf/25/2002/25_2002_2_590.pdf, last accessed 28 Feb 2007; in Dutch.)

[3] Frasch G, Anatschkowa E, Kragh P. European study of occupational radiation exposure (ESOREX). Radiat Prot Dosim 96:35–37, 2001.

[4] ESOREX: Netherlands – European Study of Occupational Exposures. (availlable as pdf document from http://www.esorex.cz/ES_003_Authorized_Area/netherlands/Netherlands.pdf, last accessed 28 Feb 2007.)

[5] 10 CFR 835, Occupational Radiation Protection, 63 FR 59662. Washington, DC: Federal Register Vol. 63,Nr. 213, 1998.
(available in pdf format from http://www.hss.energy.gov/Enforce/rands/10cfr835.pdf, last accessed 28 Feb 2007.)

[6] EDPG. External Dosimetry Program Guide for use with Title 10, Code of Federal Regulations, Part 835, Occupational Radiation Protection. DoE G 441.1-4. Washington, DC: US Department of Energy, 1999.
(available in pdf format from http://www.directives.doe.gov/pdfs/doe/doetext/neword/441/g4411-4a.pdf, last accessed 28 Feb 2007.)

[7] Van Dijk JWE. Tien jaar Nationaal Dosisregistratie- en Informatiesysteem NDRIS. Nederlandse Vereniging voor Stralingshygiëne, NVS Publicatie 30, 2000. (in Dutch)

[8] Van Dijk JWE, De Jong P. Analyse stralingsdoses NDRIS: Gegevensverzameling, indelingen en protocollen. NRG-Arnhem, Report K5098/04.063142, 2004. (in Dutch)

[9] Van Dijk JWE, Van Dijk W, De Jong P. Nieuwe systematiek voor indeling radiologische werkers. NRG-Arnhem, Report K5098/06.072971, 2006.
(available in pdf format from http://docs.szw.nl/pdf/92/2006/92_2006_1_15548.pdf, last accessed 28 Feb 2007; in Dutch.)

[10] De Jong P. Reglement privacybescherming persoonsgegevens NDRIS. NRG-Arnhem, Report NRG-RE-KD.01/I, 2002.
(available in pdf format from http://www.nrg-nl.com/docs/ndris/nrg_re_kd01.pdf, last accessed 28 Feb 2007; in Dutch.)

[11] ICRP. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60, Oxford: Pergamon Press, 1991.

[12] Harder D. Recently proposed concepts and quantities in radiation protection. In: Burger G, Ebert HG, Harder D, Kramer R, Wagner S (eds) Proceedings European Seminar on

Radiation Protection Quantities for External Exposure. Harwood Academic Publishers, for the CEC, Brussels, 1981, pp 15-31.

[13] ICRP. General principles of monitoring for the radiation protection of workers. ICRP Publication 75, Oxford: Pergamon Press, 1997.

[14] Lopez Ponte MA, Castellani CM, Currivan L, Van Dijk JWE, Falk R, Olko P and Wernli C. A catalogue of dosemeters and dosimetric services within Europe—an update. Radiat Prot Dosim 112:45-68, 2004.

[15] Bolognese-Milsztaijn T, Ginjaume M, Luszik-Bhadra M, Vanhavere F, Wahl W, Weeks A. Active personal dosemeters for individual monitoring and other new developments. Radiat Prot Dosim 112:141-168, 2004.

[16] NCRP. Use of personal monitors to estimate effective dose equivalent and effective dose to workers for external exposure to low-LET radiation. NCRP Report 122. Bethesda, MD: National Council on Radiation Protection and Measurements, 1995.

[17] Böhm J. Some remarks on accuracy and precision in individual monitoring, IAEA intercomparison for individual monitoring, Vienna, 1989. Braunschweig: PTB, Bericht PTB Dosimetry 20, 1991.

[18] Health and Safety Executive. Work with ionising radiation; Ionising Radiations Regulations 1999 Approved code of practice and guidance. Sudbury, UK: HSE Books, ISBN 0 7176 1746 7 reference L121, 2000.

[19] Dosimetrieverordnung. SR 814.501.43 Verordnung vom 7. Oktober 1999 über die Personendosimetrie. Die Bundesbehörden der Schweizerischen Eidgenossenschaft, 1999. (Swiss Ordinance on Personal Dosimetry)
(available in pdf format from http://www.admin.ch/ch/d/as/2000/840.pdf, last accessed 28 Feb 2007; in German.)

[20] De Jong P, Van Dijk JWE. Enquête naar de draaggewoonte van persoonsdosimeters. NRG-Arnhem, Report K5098/06.075759, 2006.
(available in pdf format from http://docs.szw.nl/pdf/92/2006/92_2006_1_15547.pdf, last accessed 28 Feb 2007; in Dutch.)

[21] Eleveld H and Tanzi CP. Standaardisatie van persoonsdosimetrie bij beroepsmatige blootstelling aan ioniserende straling. [Standardisation of individual monitoring for occupational exposures to ionising radiation.] RIVM Rapport 861007001. Den Haag: Ministerie van Sociale Zaken en Werkgelegenheid, Werkdocument 329, 2004.
(available in pdf format from http://docs.szw.nl/pdf/92/2004/92_2004_1_7459.pdf, last accessed 28 Feb 2007; in Dutch.)

[22] Van Dijk JWE. Statistische analyse van de dosis als gevolg van beroepsmatige blootstelling aan ioniserende straling 1993-2002. NRG-Arnhem, Report K5098/03.IM333, 2004.
(available in pdf format from http://docs.szw.nl/pdf/129/2004/129_2004_3_6049.pdf, last accessed 28 Feb 2007; in Dutch.)

[23] Van Dijk JWE. Statistische analyse van de dosis als gevolg van beroepsmatige blootstelling aan ioniserende straling 1995-2004. NRG-Arnhem, Report K5098/06.072935, 2006.

(available in pdf format from http://docs.szw.nl/pdf/129/2006/129_2006_3_9979.pdf, last accessed 28 Feb 2007; in Dutch.)

[24] Rantanen E (ed). Radiation practices. Annual Report 2002. STUK-B-STO 51. Helsinki, Finland: Radiation and Nuclear Safety Authority, June 2003.
(available in pdf format from http://www.stuk.fi/julkaisut/stuk-b/stuk-b-sto51.pdf, last accessed 28 Feb 2007.)

[25] Limacher MC, Douglas PS, Germano G, Laskey WK, Lindsay BD, McKetty MH, Moore ME, Park JK, Prigent FM, Walsh MN. Radiation safety in the practice of cardiology. J Am Coll Cardiol 31:892-913, 1998.

[26] ICRU. Determination of dose equivalents resulting from external radiation sources. ICRU Report 39. Bethesda, MD: International Commission on Radiation Units and Measurements, 1985 (reprint 2005).

[27] ICRU. Determination of dose equivalents from external radiation sources—Part II. ICRU Report 43. Bethesda, MD: International Commission on Radiation Units and Measurements, 1988.

[28] ICRU. Measurement of dose equivalents from external photon and electron radiations. ICRU Report 47. Bethesda, MD: International Commission on Radiation Units and Measurements, 1992.

[29] ICRU. Determination of operational dose equivalent quantities for neutrons. ICRU Report 66. Journal of the ICRU 1(3):1-96, 2001.

[30] ICRU. Quantities and units in radiation protection dosimetry. ICRU Report 51. Bethesda, MD: International Commission on Radiation Units and Measurements, 1993.

[31] Alberts WG and Dietze G. Proposal for a simplification of the operational quantities for routine monitoring. ICRU News, Dec 2000.
(available in pdf format from http://www.icru.org/n_002_2.pdf, last accessed 28 Feb 2007.)

[32] IAEA. Individual monitoring. Manual IAEA-PRTM-2 (Rev. 1). Vienna: International Atomic Energy Agency, 2004.

[33] Bartlett DT, Tanner RJ. Adequacy of external dosimetry methods and suitability of personal dosemeters for workplace radiation fields. Health and Safety Executive, Research Report 385, 2005.

[34] Bader FJM, Damen PMG, De Vries W, Pieksma MWH. Tweede nationale vergelijking van erkende diensten voor persoonsdosimetrie (Second national intercomparison of accredited personal dosimetric services, in Dutch). NMi Report S-SL-IO-2004.02, Utrecht: NMi Nederlands Meetinstituut, 2004.

[35] Lund E, Kyllonen JE, Grindborg JE, Lindborg L. Performance testing of personal dosemeters from eleven dosimetry services in Sweden. Radiat Prot Dosim 96:99–103, 2001.

[36] Bordy JM, Stadtmann H, Ambrosi P, Bartlett DT, Christensen P, Colgan T, Hyvonen H. Performance test of dosimetric services in the EU Member States and Switzerland for the routine assessment of individual doses (photon, beta and neutron). Radiat Prot Dosim 89:107-154, 2000.

[37] IAEA. Intercomparison for Individual Monitoring of External Exposure from Photon Radiation. IAEA-TECDOC-1126. Vienna: International Atomic Energy Agency, 1999.

[38] EC. Technical recommendations for monitoring individuals occupationally exposed to external radiation. Radiation Protection 73. Report EUR 14852 EN. Luxemburg: Office for Official Publications of the European Communities, 1994.

[39] Bartlett DT, Ambrosi P, Bordy JM, Van Dijk JWE (eds) Harmonisation and dosimetric quality assurance in individual monitoring for external radiation. Radiat Prot Dosim 89: 1–154, 2000.

[40] Koninklijk besluit van 20 juli 2001 houdende algemeen reglement op de bescherming van de bevolking, van de werknemers en het leefmilieu tegen het gevaar van de ioniserende stralingen. Belgisch Staatsblad van 30.08.2001, pp 28906-29368.
(available in pdf format from www.fanc.fgov.be/download/reglementation_20_07_2001_nl.pdf, and www.fanc.fgov.be/newfanc/download/reglementation_20_07_2001_annexes_nl.pdf; last accessed 28 Feb 2007; in Dutch.)

[41] Chumak VV, Bakhanova EV. Relationship between protection and operational quantities in dosimetry of photon external exposure—deficiencies of $H_P(10)$. Radiat Prot Dosim 104:103–111, 2003.

[42] Faulkner K, Marshall NW. The relationship of effective dose to personnel and monitor reading for simulated fluoroscopic irradiation conditions. Health Phys 64:502–508, 1993.

[43] Ambrosi P, Fantuzzi E, De Carvalho AF, Delgado A, Lindborg L, Bartlett DT. Procedures for routine individual dose assessment of external radiation within EU countries and Switzerland—Status of harmonisation on 1 April 1999. Radiat Prot Dosim 89:7-51, 2000.

[44] Michel R, Perle SC. Effective dose equivalent estimates in diagnostic radiology with single dosimetry. Health Phys 79:(Suppl.)S17–S19, 2000.

[45] Kicken PJH. In: Broerse JJ, Kicken PJH, Teeuwisse W, De Vries W, Zoetelief J, Zweers D. Dosimetrie in de radiologie – stralingsbelasting van de patiënt en werknemers. Chapter 6, Stralingsdosimetrie voor werknemers. NCS report 17. Delft: Nederlandse Commissie voor Stralingsdosimetrie, 2007 (in Dutch).

[46] Kicken PJH, Bos AJJ. Effectiveness of lead aprons in vascular radiology: results of clinical measurements. Radiology 197:473–478, 1995.

[47] Järvinen H, Buls N, Clerinx P, Jansen J, Miljanić S, Nikodemová D, Ranogajec-Komor M, D'Errico F. Overview of double dosimetry procedures for the determination of effective dose to the interventional radiology staff. Radiat Prot Dosim 129:333-339, 2008.

[48] Franken Y, Huyskens CJ. Guidance on the use of protective lead aprons in medical radiology: protection efficiency and correction factors for personal dosimetry. Paper 17, 6th European ALARA Network Workshop, Madrid, Spain, 2002.
(Available in pdf format from http://ean.cepn.asso.fr/pdf/program6/Session%20E/Y_Franken.pdf; last accessed 28 Feb 2007.)

[49] Tsapaki V, Kottou S, Vano E, Komppa T, Padovani R, Dowling A, Molfetas M, Neofotistou V. Occupational dose constraints in interventional cardiology procedures: the DIMOND approach. Phys Med Biol 49:997–1005, 2004.

[50] Wambersie A, Delhove J. Radiation protection in diagnostic radiology, a debated practice: how to wear the individual dosemeters? J. Belge Radiol 76:382-385, 1993.

[51] Rosenstein M, Webster EM. Effective dose to personnel wearing protective aprons during fluoroscopy and interventional radiology. Health Phys 67:88-89, 1994.

[52] Niklason LT, Marx MV, Chan HP. The estimation of occupational effective dose in diagnostic radiology with two dosimeters. Health Phys. 67:611–615, 1994.

[53] McEwan AC. Assessment of occupational exposure in New Zealand from personal monitoring records. Radiat Prot in Australasia 17:60-66, 2000.

[54] Sherbini S, DeCicco J. Estimation of effective dose when protective aprons are used in medical procedures: A theoretical evaluation of several methods. Health Phys 83:861-870, 2002.

[55] Von Bötticher H, Lachmund J, Hoffmann W, Luska G. Strahlenexposition des Personals in Röntgendiagnostik: Bestimmung der effektiven Dosis mit dem 2-Dosimeter-Verfahren. Proc Jahrestagung Dortmund, 12-15/10/2003, “Strahlenschutz bei medizinischen Anwendungen” pp 109-113, ISBN 3-00-012084-X, 2003 (in German).

[56] Lachmund J. Zur Quantifizierung der biologisch relevanten Stralenexposition von Beschäftigten in Radiologie und Kardiologie. PhD Thesis, Bremen University, 2005 (in German).

[57] Clerinx P, Buls N, Bosmans H, De Mey J. Double dosimetry algorithm for workers in interventional radiology. Radiat Prot Dosim 129:321-327, 2008.

[58] Huyskens CJ, Franken Y, Hummel WA. Guidance on personal dosimetry for occupational exposure in interventional radiology. J Radiol Prot 14:229–234, 1994.

[59] Schultz FW, Geleijns J, Spoelstra FM, Zoetelief J. Monte Carlo calculations for assessment of radiation dose to patients with congenital heart defects and to staff during cardiac catheterizations. Br J Radiol 76:638-647, 2003.

[60] Schultz FW, Zoetelief J. Dosemeter readings and effective dose to the cardiologist with protective clothing in a simulated interventional procedure. Radiat Prot Dosim 129:311-315, 2008.

[61] Struelens L. SCK-CEN, Mol, Belgium. Personal communication, 2006.

[62] Kicken PJH. Radiation dosimetry in vascular radiology: Organ and effective dose to patients and staff. Thesis. Maastricht: Maastricht University, 1996.

[63] Mateya CF, Claycamp HG. Phantom-derived estimation of effective dose equivalent from X rays with and without a lead apron. Health Phys 74:489–491, 1998.

[64] Kicken PJH, Kemerink GJ, Schultz FW, Zoetelief J, Broerse JJ, Van Engelshoven JMA. Dosimetry of Occupationally Exposed Persons in Diagnostic and Interventional Arteriography. Part 2: Assessment of Effective Dose. Radiat Prot Dosim 82:105-114, 1999.

[65] Padovani R, Foti C, Malisan MR. Staff dosimetry protocols in interventional radiology. Radiat Prot Dosim 94:193–196, 2001.

[66] Maeder M, Verdun FR, Stauffer JC, Ammann P, Rickli H. Radiation exposure and radiation protection in interventional cardiology (Review). Kardiovaskuläre Medizin 8:124-132, 2005.

[67] Stichting DBC Onderhoud. Instructie DBC-registratie Radiologie / Interventieradiologie. Amsterdam, 2005.
http://www.dbconderhoud.nl/_downloads/instr_radiol050610.doc; last accessed 28 Feb 2007; in Dutch.

[68] RIVM. Informatiesysteem Medische Stralingstoepassingen.
http://www.rivm.nl/ims, last accessed 28 Feb 2007; in Dutch.

[69] Brugmans MJP, Lembrechts J. Informatiesysteem Medische Stralingstoepassingen: een pilotstudie. RIVM Rapport 610059008, juli 2001. (in Dutch)

[70] Spoelstra FM, Geleijns J. Leiden University Medical Center, Leiden, The Netherlands. Personal communication, 2002.

[71] Zoetelief J, Faulkner K. Equipment requirements and specification for digital and interventional radiology. Radiat Prot Dosim 94:43–48, 2001.

[72] NCRP. Radiation Protection in Veterinary Medicine. NCRP Report 148. Bethesda, MD: National Council on Radiation Protection and Measurements, 2005.

[73] State of California—Department of Health Services/Radiologic Health Branch. Veterinary safety instructions. Provided to CMVA, November, 1998.
(Available in pdf format from http://www.cvma.net/images/cvmapdf/Radiation.pdf, last accessed 28 Feb 2007.)

[74] CVO College of Veterinarians of Ontario. Radiation protection and monitoring for veterinarians, veterinary clinic employees and clients. INFO Sheet, March 2003.
(Available in pdf format from http://www.cvo.org/uploadattachments/RadiationProtectionandMonitoring.pdf, last accessed 28 Feb 2007.)

[75] University of Pennsylvania Radiation Safety Office. Veterinary energized equipment user's guide.
http://www.ehrs.upenn.edu/programs/radiation/guides/VetEnerEquip.html, last accessed 28 Feb 2007.

[76] The Four Pillars of Veterinary Radiation Safety.
http://www.animalinsides.com, last accessed 28 Feb 2007.

[77] ARPANSA. DRAFT Code of practice: Safe use of radiation in veterinary science. (Radiation Protection Series Publication No. ?? Public Consultation Version: February 2005). Yallambie, Victoria, Australian Radiation Protection and Nuclear Safety Agency
(available as pdf from http://www.arpansa.gov.au/pubs/comment/vet_dft.pdf, last accessed 28 Feb 2007.)

[78] De Jong P, Van Dijk W, Timmermans CWM. Classificatie ioniserende straling uitzendende toestellen. (NRG-Arnhem). Report K5098/03.IM327, 2003.
(available in pdf format from http://docs.szw.nl/pdf/4/2004/4_2004_1_6338.pdf, last accessed 28 Feb 2007; in Dutch.)

[79] IAEA. International basic safety standards for protection against ionizing radiation and for the safety of radiation sources. Safety Series No. 115. Vienna: International Atomic Energy Agency, 1996.

[80] IAEA. Occupational radiation protection safety guide. Safety Standards Series No. RS-G-1.1. Vienna: International Atomic Energy Agency, 1999.

[81] IAEA. Assessment of Occupational Exposure due to External Sources of Radiation Safety Guide. Safety Standards Series No. RS-G-1.3. Vienna: International Atomic Energy Agency, 1999.

[82] IAEA. Personal Protective Equipment. IAEA-PRTM-5. Vienna: International Atomic Energy Agency, 2004.

[83] Marshall NW, Faulkner K, Clarke P. An investigation into the effect of protective devices on the dose to radiosensitive organs in the head. Brit J Radiol 65:799–802, 1992.

[84] Eder H, Panzer W, Schöfer H. Ist der Bleigleichwert zur Beurteilung der Schutzwirkung bleifreier Röntgenschutzkleidung geeignet? Fortschr Röntgenstr 177:399-404, 2005.

[85] Finnerty M, Brennan PC. Protective aprons in imaging departments: manufacturer stated lead equivalence values require validation. Eur Radiol 15:1477-1484, 2005.

[86] Kuon E, Birkel J, Schmitt M, Dahm JB. Radiation exposure benefit of a lead cap in invasive cardiology. Heart 89:1205–1210, 2003.

[87] King JN, Champlin AM, Kelsey CA, Tripp DA. Using a sterile disposable protective surgical drape for reduction of radiation exposure to interventionalists. Am J Roentgenology. 178:153–157, 2002.

[88] Lemer Pax. The Cathpax radiation protection cabin.
http://www.lemerpax.com/PDF/XRAY/Cathpax.pdf, last accessed 5 Feb 2008.