Chapter 22: Patient Dosimetry

Slide set of 196 slides based on the chapter authored by D.R. Dance and I. Castellano of the IAEA publication (ISBN 978-92-0-131010-1):

Diagnostic Radiology Physics: A Handbook for Teachers and Students

Objective:

To familiarize the student with terminology and practical issues associated with patient dosimetry.

IAEA
International Atomic Energy Agency

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22.1 INTRODUCTION

22.1

Introduction

- Patient exposures arising from radiological procedures form the largest part of the population exposure from man-made sources of radiation
- The annual frequency of X ray examinations is 360 per 1000 individuals worldwide (UNSCEAR)
- The associated risk of radiation detriment to the patient means there is a clear need to reduce the patient dose as possible, consistent with the required clinical image quality:
  - monitor and control these exposures
  - optimize the design and use of the X ray imaging equipment

Dosimetric quantities

- The dosimetric quantities used in diagnostic radiology can be divided into two broad groups:
  - Application specific quantities: these are practical dosimetric quantities which may be directly measured and which may be tailored to specific situations or modalities
    - examples include incident air kerma, air kerma-area product and CT air kerma indices
  - Risk related quantities: these are dosimetric quantities which can be used to estimate radiation detriment or risk and are thus measures of absorbed dose
    - examples include organ dose and mean glandular dose (for mammography)

Measurements of application specific quantities

- In some situations it is desirable to make direct measurements of the application specific quantities
- For others it is preferable to make measurements using a standard phantom to simulate the patient
  - examples include quality control, the comparison of different systems and optimization studies
- The measurement methodology used depends upon the type of examination
- A detailed description of the measurement methodology can be found in the IAEA Code of Practice for Dosimetry in Diagnostic Radiology, Report TRS 457

Measurements of risk-related quantities

- Risk-related quantities are usually difficult to measure directly
- Generally estimated from application specific quantities using tables of dose conversion coefficients, determined either
  - by Monte Carlo calculation or
  - measurements using phantoms

Dose limits and diagnostic reference levels

- Dose limits are used to control the exposure of workers and members of the public to ionizing radiation
- However dose limits for medical exposures could have a detrimental effect on patients' health through failure to obtain essential clinical information
- Therefore patient doses are managed rather than controlled
- The primary tool is the diagnostic reference level

22.2 APPLICATION SPECIFIC QUANTITIES

22.2

22.2 APPLICATION SPECIFIC QUANTITIES

22.2

Application specific quantities

- 22.2.1 Incident air kerma
- 22.2.2 Entrance surface air kerma
- 22.2.3 X ray tube output
- 22.2.4 Air kerma-area product
- 22.2.5 Air kerma-length product
- 22.2.6 Quantities for CT dosimetry

Risk-related quantities

- 22.2.7 Organ and tissue dose
- 22.2.8 Mean glandular dose
- 22.2.9 Equivalent dose
- 22.2.10 Effective dose

Introduction to application specific quantities (1 of 2)

- Application specific quantities are practical dosimetric quantities for particular X ray modalities that are used for measurements in diagnostic radiology
- Various specific quantities have been found useful in the past but there has been ambiguity in the names of the quantities and their (sometimes incorrect) use
- In the following slides we follow the recommendations of ICRU Report 74 also adopted in the IAEA Report TRS 457

Introduction to application specific quantities (2 of 2)

- Air kerma is used as the basis of all application specific quantities
- The SI unit for air kerma is the gray (Gy)

- In the past, the quantity exposure (old unit: roentgen (R)) was used instead of air kerma
- Values of exposure in roentgen can be converted to air kerma in gray using the conversion 0.876×10^{-2} Gy/R (ICRU 47, 1992)

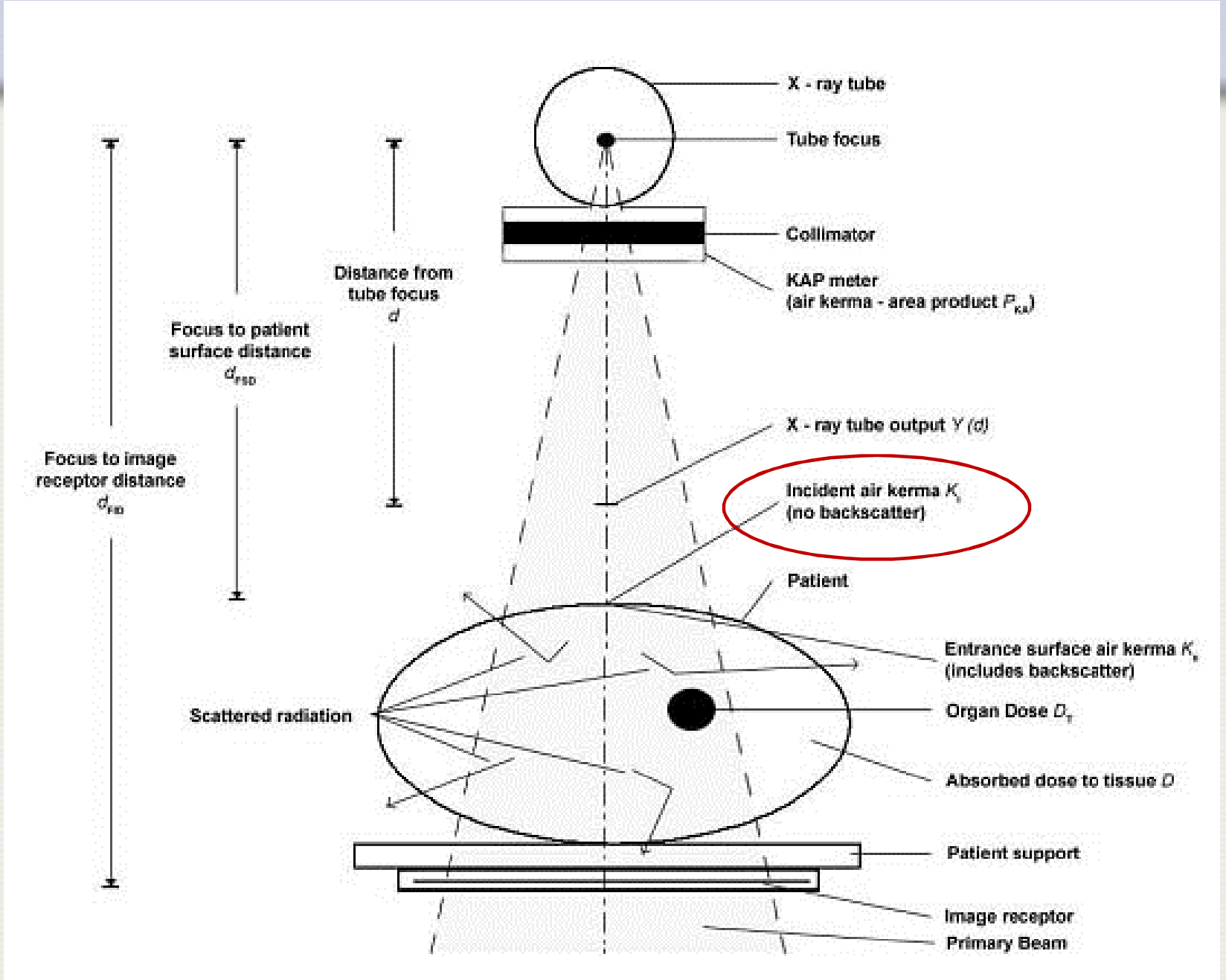
22.2 APPLICATION SPECIFIC QUANTITIES

22.2.1 INCIDENT AIR KERMA

Incident air kerma

- The incident air kerma, $K_{i,}$, is the simplest application specific quantity to measure
- It is particularly useful in situations where the X ray field parameters remain unchanged throughout the exposure
  - such as plain-film radiography
- It is defined as the kerma to air from an incident X ray beam measured on the central beam axis at the position of the patient or phantom surface (see Figure)
- Only radiation incident on the patient or phantom is included – and not the backscattered radiation

22.2 APPLICATION SPECIFIC QUANTITIES



22.2 APPLICATION SPECIFIC QUANTITIES

22.2.2 ENTRANCE SURFACE AIR KERMA

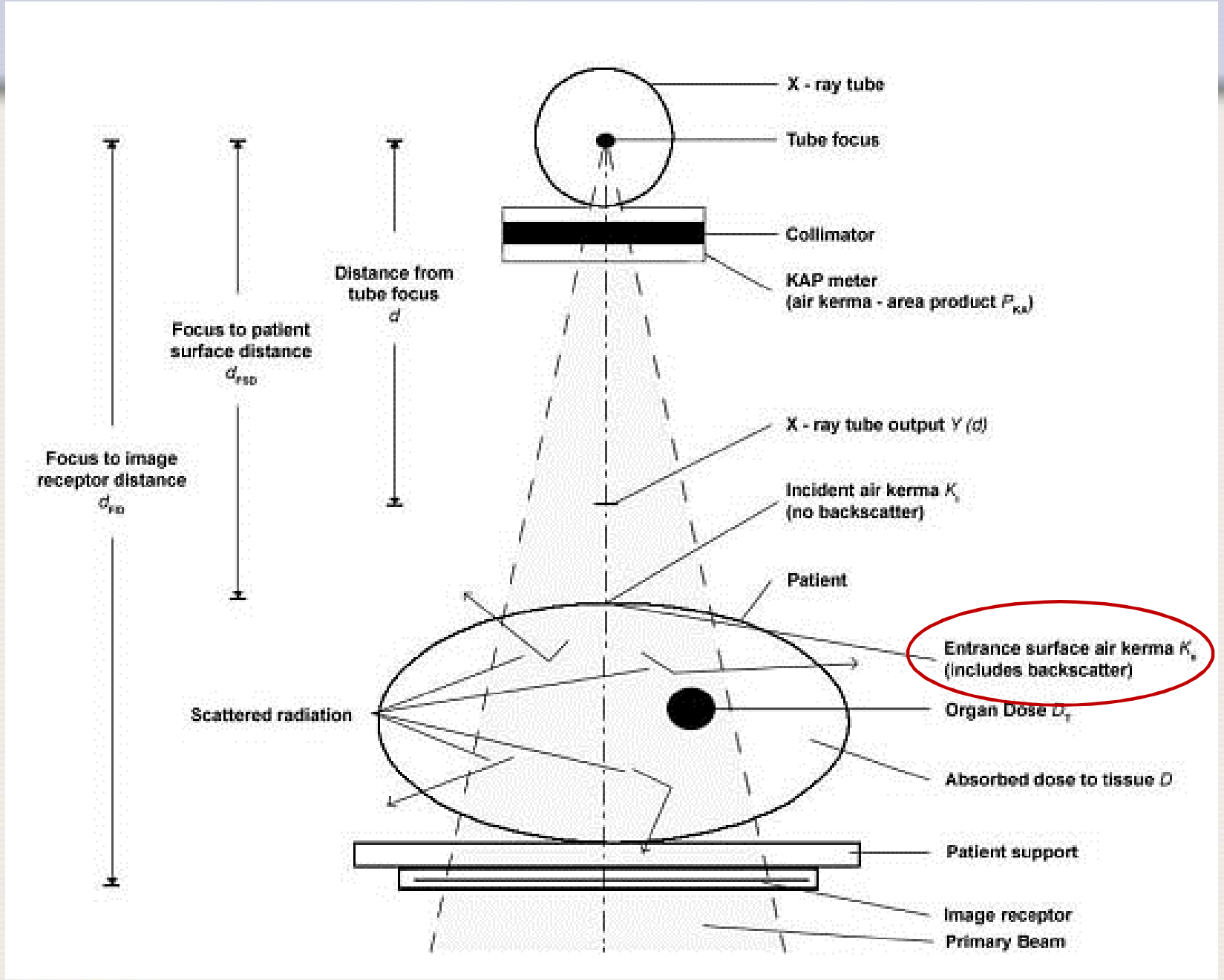
22.2 APPLICATION SPECIFIC QUANTITIES

22.2.2 Entrance surface air kerma

Entrance surface air kerma

- In some situations (for example measurements at the patient surface), backscattered radiation is included in the measurement
- The measured quantity is then known as the entrance surface air kerma, K_e
- This is defined as the kerma to air measured on the central beam axis at the position of the patient or phantom surface (see Figure)
- The radiation incident on the patient or phantom and the backscattered radiation are included in the measurement

22.2 APPLICATION SPECIFIC QUANTITIES



Entrance surface air kerma estimation

- When the entrance surface air kerma is not measured directly it can be estimated using the relationship:

$$K_e = K_i B$$

where B is the backscatter factor

- The backscatter factor depends upon the
  - field size
  - radiation quality
  - backscatter material
- It can be obtained from published tables or can be measured using phantoms

Entrance surface air kerma rate

- For procedures such a fluoroscopy and fluorography
  - the exposure time can vary considerably from patient-to-patient
- It can be important to determine the entrance surface air kerma rate because of the potential for giving very high skin doses
- In most countries there will be a limit to the maximum air kerma rate which can be used for fluoroscopy

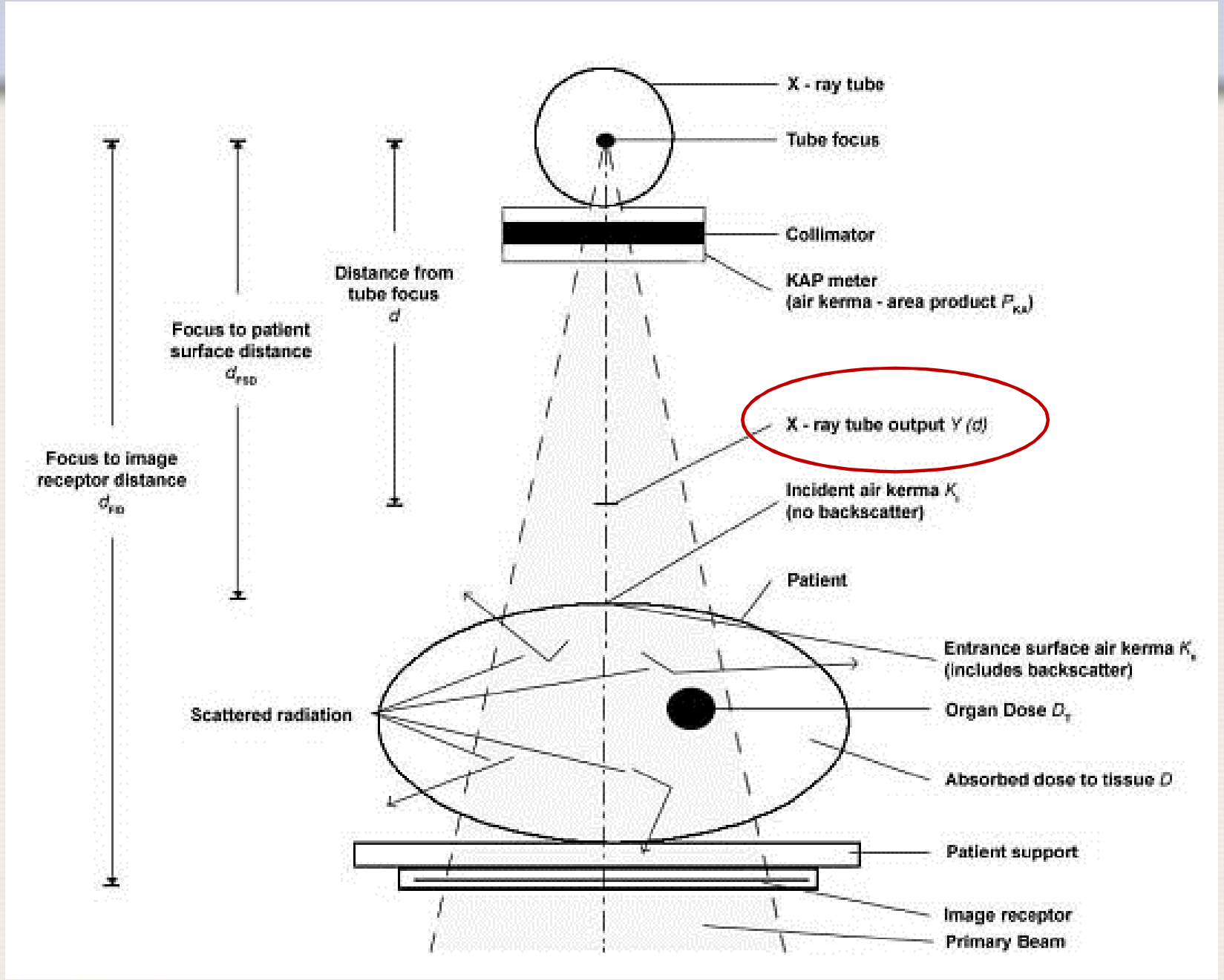
22.2 APPLICATION SPECIFIC QUANTITIES

22.2.3 X-RAY TUBE OUTPUT

X-ray tube output

- It is sometimes not possible to measure the incident or entrance surface air kerma directly
- These quantities can then be estimated from measurements of the tube output with knowledge of the exposure parameters for the examination
- The X ray tube output, $Y(d)$, is defined as the quotient of the air kerma $K(d)$ at a specified distance, d, from the X ray tube focus and the tube current-exposure time product P_{It}
- See Figure

22.2 APPLICATION SPECIFIC QUANTITIES



22.2 APPLICATION SPECIFIC QUANTITIES

22.2.3 X-ray tube output

$$Y(d) = \frac{K(d)}{P_{It}}$$

where

- $K(d)$ is the air kerma at distance d from X-ray tube focus
- P_{It} is tube current-exposure time product (sometimes referred to as the “tube loading” or the “mAs”)

- Tube output ($Y(d)$) is usually expressed in units of mGy.mAs^{-1}
- The incident air kerma for a particular exposure X is estimated from the tube output and the tube loading for the exposure $P_{It}(X)$ by applying the inverse square law

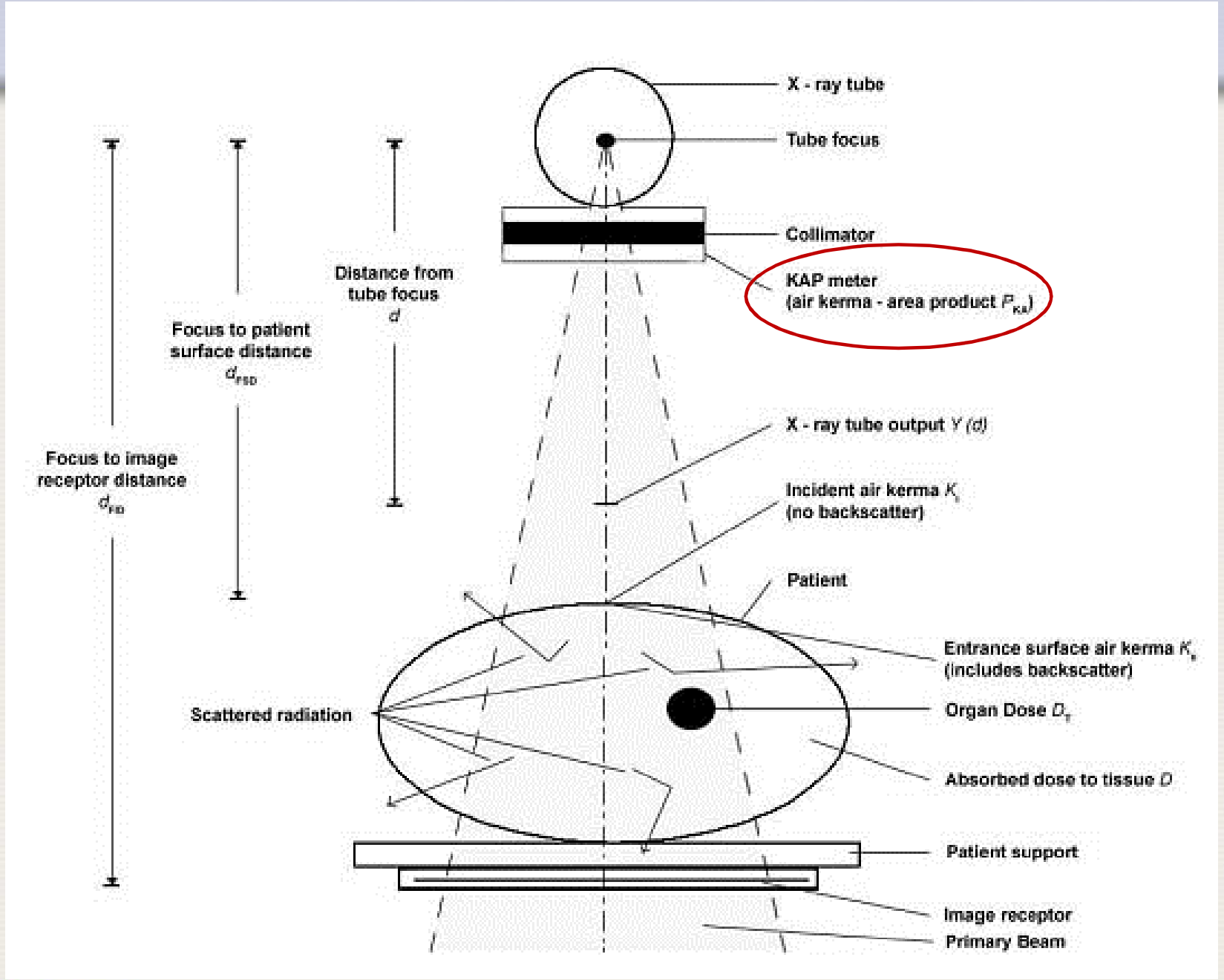
22.2 APPLICATION SPECIFIC QUANTITIES

22.2.4 AIR KERMA-AREA PRODUCT

Air kerma-area product

- In examinations such as fluoroscopy, where the beam direction, tube voltage, field size and tube current vary throughout the exposure, the incident air kerma is not a good measure of radiation detriment
- The air kerma-area product P_{KA} may be used instead
- It is defined as the integral of the air kerma over the area of the X ray beam in a plane perpendicular to the beam axis (see Figure)

22.2 APPLICATION SPECIFIC QUANTITIES



22.2 APPLICATION SPECIFIC QUANTITIES

22.2.4 Air kerma-area product

$$P_{KA} = \int_A K(x,y)\mathrm{d}x\mathrm{d}y$$

where

- $K(x,y)$ is the air kerma
- A the area of the X ray beam in a plane perpendicular to the beam axis

- Air kerma-area product is usually expressed in units of cGy.cm^2, μGy,cm^2 or mGy.cm^2
- Generally measured using a plane transmission ionization chamber known as a KAP-meter
- In the approximation that the air kerma does not vary across the radiation field
  - P_{KA} is equal to the product of the air kerma and field area

KAP and distance from X ray tube focus

- When interactions in air and extra-focal radiation can be neglected
- The air kerma-area product (KAP) is approximately independent of the distance from the X ray tube focus
  - as long as the planes of measurement and calculation are not so close to the patient or phantom that there is a significant contribution from backscattered radiation

22.2 APPLICATION SPECIFIC QUANTITIES

22.2.5 AIR KERMA-LENGTH PRODUCT

Air kerma-length product

- In some situations a useful alternative to P_{KA} is the air kerma-length product, P_{KL}
- The integral of the air kerma, $K(x)$, along a line, L

$$P_{KL} = \int_{L} K(x)\mathrm{d}x$$

- P_{KL} is usually expressed in units of mGy.cm
- It is used for the dosimetry in CT and in panoramic dentistry, where it is also referred to as the KLP

22.2 APPLICATION SPECIFIC QUANTITIES

22.2.6 QUANTITIES FOR CT DOSIMETRY

Quantities for CT dosimetry

- The irradiation conditions in CT are quite different from those in planar imaging and it is necessary to use special dosimetric quantities and techniques
- Measurements may be made free-in air or in-phantom
- The dosimetric quantities for both are referred to as computed tomography kerma indices and are based on measurements of P_{KL}
- A pencil ionization chamber is generally used

Terminology for CT dosimetry

- Both types of measurement have in the past been expressed in terms of a 'Computed Tomography Dose Index' (CTDI)
  - however, for measurements 'in-phantom' using an air kerma calibrated ionization chamber, the measured quantity is air kerma
  - the absorbed dose to an air cavity within a phantom arises from a situation without secondary electron equilibrium and is difficult to measure
- For these reasons, the terminology 'Computed Tomography Kerma Index' is used here for both free-in air and in-phantom measurements
  - this is in accordance with ICRU 74
- All of the CT kerma indices used correspond directly with those previously referred to as CTDI related quantities

CT kerma index free-in-air (1 of 2)

- The CT kerma index $C_{a,100}$, measured free-in-air for a single rotation of a CT scanner is
  - the quotient of the integral of the air kerma along a line parallel to the axis of rotation of a CT scanner over a length of 100 mm and the product of the number of simultaneously acquired tomographic sections, *N*, and the nominal section thickness, *T*
  - The integration range is positioned symmetrically about the volume scanned

$$C_{a,100} = \frac{1}{NT}\int_{-50}^{+50} K(z)\,dz$$

  - $C_{a,100}$ is usually expressed in units of mGy
  - For in-phantom measurements the notation $C_{PMMA,100}$ is used

CT kerma index free-in-air (2 of 2)

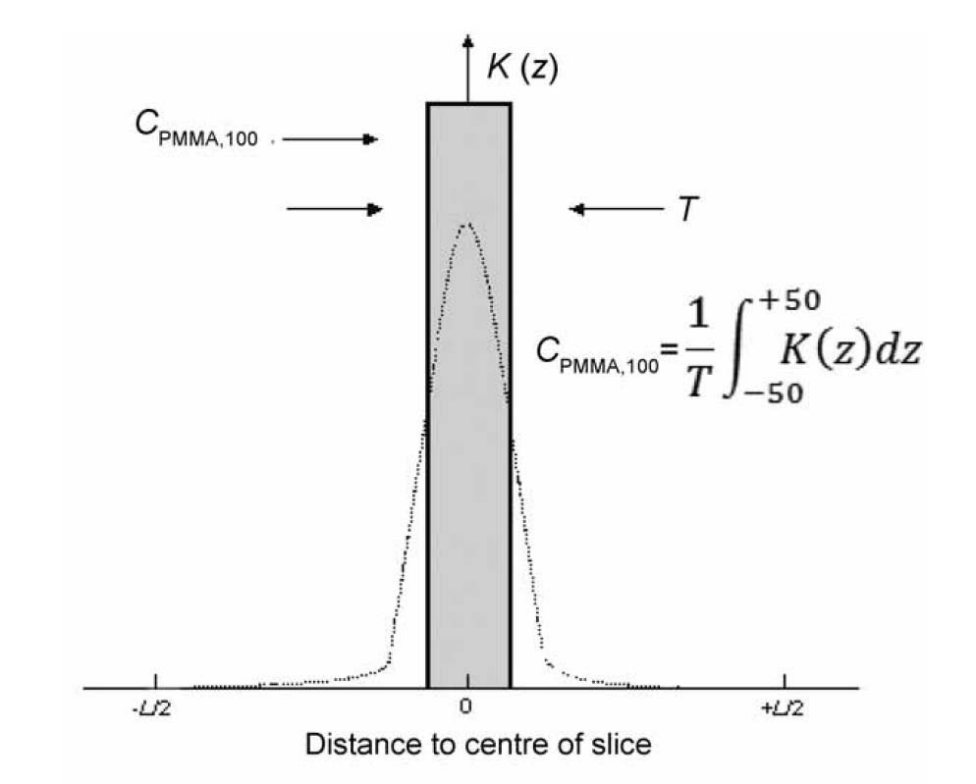
$$C_{a,100} = \frac{1}{NT}\int_{-50}^{+50} K(z)dz$$

- From the equation it can be seen that the CT air kerma index is the height of a rectangular air kerma profile of width equal to the product of
  - the number of sections, N, and
  - the nominal section thickness, *T*, that has the same value as the line integral
- For a single slice scanner – see Figure

22.2 APPLICATION SPECIFIC QUANTITIES

22.2.6 Quantities for CT dosimetry

- Profile of the air kerma $K(z)$ in a CT dosimetry phantom along an axis (z) for a single CT slice of nominal width T mm
- The CT kerma index $C_{PMMA,100}$ is obtained by integrating the air kerma over a length of 100 mm



Weighted CT kerma index in phantom (1 of 2)

- Unlike some areas of dosimetry, only two phantoms have found common application
  - the standard head and body phantoms
- The weighted CT kerma index, C_W, combines values of $C_{100,PMMA}$ measured at the centre and periphery of these phantoms

Weighted CT kerma index in phantom (2 of 2)

$$C_W = \frac{1}{3}\left(C_{PMMA,100,c} + 2C_{PMMA,10,p}\right)$$

- $C_{PMMA,100,c}$ is measured at the centre of the standard CT dosimetry phantom
- $C_{PMMA,100,p}$ is the average of values measured at four positions around the periphery of the phantom

- The weighted CT kerma index is an approximation to the average air kerma in the volume of the phantom interrogated by a single rotation of the scanner

Volume averaged weighted CT kerma index in phantom

- C_{VOL} provides a volume average which takes account of the helical pitch or axial scan spacing

$$C_{VOL} = \frac{C_W NT}{l} = \frac{C_W}{p}$$

where

- N is the number of simultaneously acquired tomographic sections
- T the nominal slice thickness
- l is the distance moved by the patient couch per helical rotation or between consecutive scans for a series of axial scans
- P_{It} is the tube loading for a single axial scan
- p is the CT pitch factor (or pitch) for helical scanning

CT pitch factor

- p is the CT pitch factor (or pitch) for helical scanning

$$p = \frac{l}{NT}$$

where

- l is the distance moved by the patient couch per helical rotation or between consecutive scans for a series of axial scans
- N is the number of simultaneously acquired tomographic sections
- T the nominal slice thickness

Volume averaged weighted CT kerma index in phantom

- The quantity ${}_nC_{VOL}$ is normalized to unit tube current-exposure time product

$$ {}_nC_{VOL} = \frac{C_{VOL}}{P_{It}} $$

where

- P_{It} is the tube loading for a single axial scan

CT air kerma-length product

- The CT air kerma index C_{VOL}, (or the index C_W) can be combined with patient exposure parameters to provide a dose measure for a complete patient examination
- The CT air kerma-length product $P_{KL,CT}$

$$P_{KL,CT} = \sum_j {}_n C_{VOL} l_j P_{It_j}$$

where

- the index j represents each serial or helical scan sequence forming part of the examination
- l_j is the distance moved by the patient couch between or during consecutive scanner rotations and is the total tube loading for scan sequence j

Dosimetry in wide cone beam scanners (1 of 3)

- It has been found that the preceeding CT kerma quantities will lead to underestimates of patient dose when the width of the rotating X ray field approaches or exceeds 40 mm
- In this case C_W can be determined using …

Dosimetry in wide cone beam scanners (2 of 3)

$$C_{w,N.T} = C_{w,Ref} \times \left(\frac{C_{a,100,N.T}}{C_{a,100,Ref}} \right)$$

where

- $C_{w,N.T}$ is the weighted CT air kerma index for a beam width of N.T mm (if N.T is > 40 mm)
- $C_{w,Ref}$ is the weighted CT air kerma index for a reference beam width of 20 mm (or closest possible below 20 mm)
- $C_{a,100,N.T}$ is the CT air kerma index measured free in air for a beam width of N.T mm
- $C_{a,100,Ref}$ is a similar quantity at the reference beam width

Dosimetry in wide cone beam scanners (3 of 3)

- The methodology used to measure $C_{a,100,N.T}$ can be found in
  - INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Computed Tomography Dosimetry for Wide Cone Beam Scanners, Human Health Report No. 5, IAEA Vienna (2011). http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1528_web.pdf - accessed 25 June 2012

22.2 APPLICATION SPECIFIC QUANTITIES

22.2 RISK RELATED QUANTITIES

Risk Related Quantities (1 of 2)

- The detriment arising from medical X ray examinations
  - can be stochastic or non-stochastic (deterministic)
  - depends upon the dose to individual organs
- For stochastic effects, the total risk is the sum of the organ and tissue doses multiplied by appropriate risk coefficients
- For deterministic effects the nature and magnitude of the effect is determined by the dose to the organs or tissues concerned
- Thus the dose to individual organs and tissues has to be quantified in order to assess detriment

Risk Related Quantities (2 of 2)

- With the exception of localized skin dose, it is not possible (or at best very difficult) to measure such doses directly
- Use is made instead of combination of
  - application specific quantities
  - absorbed dose conversion coefficients derived from Monte Carlo calculations or phantom measurements
- In practice phantom measurements of coefficients are little used because of
  - the general availability of Monte Carlo calculated factors
  - the practical difficulties associated with such measurements

22.2 APPLICATION SPECIFIC QUANTITIES

22.2.7 ORGAN AND TISSUE DOSE

22.2 APPLICATION SPECIFIC QUANTITIES

22.2 Risk Related Quantities

Application specific quantities

- 22.2.1 Incident air kerma
- 22.2.2 Entrance surface air kerma
- 22.2.3 X ray tube output
- 22.2.4 Air kerma-area product
- 22.2.5 Air kerma-length product
- 22.2.6 Quantities for CT dosimetry

Risk-related quantities

- 22.2.7 Organ and tissue dose
- 22.2.8 Mean glandular dose
- 22.2.9 Equivalent dose
- 22.2.10 Effective dose

Organ and tissue dose

- The mean absorbed organ dose, D_T, in a specified organ or tissue is equal to the ratio of the energy imparted, $\bar{\varepsilon}_T$, to the tissue or organ and the mass, m_T, of the tissue or organ

$$D_T = \frac{\bar{\varepsilon}_T}{m_T}$$

- The mean absorbed dose to a specified organ or tissue is sometimes simply referred to as the organ dose

Organ and tissue dose – organs of interest

- Organs that commonly require individual dose determination include the uterus and the lens of the eye
- It is important to remember that organs may be only partly exposed to the incident radiation field and that the dose distribution within the body is far from homogeneous
- In some situations the local absorbed dose in an organ or tissue may considerably exceed the mean absorbed dose
  - for example, coronary angiography
  - it can be desirable to estimate local dose values as well the mean organ dose

Organ and tissue dose in interventional radiology

- The assessment of the absorbed dose to the most exposed area of the skin is essential in interventional radiology
  - because of the possibility for complicated procedures of exceeding the threshold for deterministic effects
- Knowledge of skin dose
  - during such procedures is necessary to avoid deterministic effects and reduce their severity
  - after the procedure is necessary for appropriate management of the patient

22.2 APPLICATION SPECIFIC QUANTITIES

22.2.8 MEAN GLANDULAR DOSE

22.2 APPLICATION SPECIFIC QUANTITIES

22.2.8 Mean glandular dose

Mean glandular dose

- The ICRP and the ICRU recommend the use of the mean (or average) dose to the glandular tissues within the breast for breast dosimetry in diagnostic radiology
  - these are the tissues which are at the highest risk of radiation induced carcinogenesis
  - this recommendation has been generally adopted.
- The acronym MGD for the mean glandular dose is used here
- Glandular tissues include the acinar and ductal epithelium and associated stroma

22.2 APPLICATION SPECIFIC QUANTITIES

22.2.9 EQUIVALENT DOSE

Equivalent dose

- Different types of ionizing radiation can cause stochastic effects of different magnitudes for the same value of the absorbed dose
- To allow for this, the equivalent dose, H_T, to an organ or tissue, T, is used
- For a single type of radiation, R, it is the product of a radiation weighting factor, w_R, and the organ dose, D_T

$$H_T = w_R D_T$$

Radiation weighting factor

- The radiation weighting factor, w_R, represents the relative biological effectiveness of the incident radiation in producing stochastic effects at low doses in tissue or organ, T
- In diagnostic radiology, w_R is usually taken to be unity
- The SI unit for equivalent dose is the sievert (Sv)

22.2 APPLICATION SPECIFIC QUANTITIES

22.2.10 EFFECTIVE DOSE

Effective dose (1 of 2)

- The radiation exposure of the organs and tissues of the human body results in different probabilities of detriment
  - for the different organs
  - for different individuals
- For radiation protection purposes, the ICRP has introduced the effective dose, E
- A measure of the combined detriment from stochastic effects for all organs and tissues for a typical reference man

Effective dose (2 of 2)

- Effective dose is the sum over all the organs and tissues of the body of the product of the equivalent dose, H_T, to the organ or tissue and a tissue weighting factor, w_T, for that organ or tissue

$$E = \sum_{\mathrm{T}} w_{\mathrm{T}} H_{\mathrm{T}}$$

Tissue weighting factor

- The tissue weighting factor, w_T, for organ or tissue T represents the relative contribution of that organ or tissue to the total 'detriment' arising from stochastic effects for uniform irradiation of the whole body
- The sum over all the organs and tissues of the body of the tissue weighting factors, w_T, is unity
- The SI unit for effective dose is the sievert (Sv)
  - this is the same unit as for equivalent dose, and care should be taken to indicate which quantity is being used

22.2 APPLICATION SPECIFIC QUANTITIES

22.2.10 Effective dose

Tissue or organ	Tissue weighting factor (w_T)	$\sum w_T$
Bone-marrow, colon, lung, stomach, breast, remainder tissues*	0.12	0.72
Gonads	0.08	0.08
Bladder, oesophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04

* The tissue weighting factor for remainder tissues is applied to the arithmetic mean of the doses to the following fourteen organs/tissues: adrenals, extrathoracic region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus and uterus/cervix

Tissue weighting factors according to ICRP Report 103

Tissue weighting factors in ICRP Report 103

- Values in the table estimated by the ICRP on the basis of
  - population studies of cancer induction
  - hereditary effects
- Averaged over age and sex for a particular population
  - because of this averaging process, the risk factors used can be quite different from the values appropriate to a particular individual undergoing an X ray examination
- It is therefore strongly emphasized that effective dose should not be used directly to estimate detriment for individual medical exposures
- Instead use risk values for the individual tissues and organs at risk and for the age distribution and sex of the individual or population being exposed (such as those tabulated in BEIR VII)

Effective dose for comparisons

- Notwithstanding this caveat, effective dose can be very useful for comparative purposes
- For example between procedures carried out with different exposure parameters or carried out in a given population
- Care should be taken when comparing values of effective dose to ensure that the same values of the tissue weighting factors w_T have been used
  - prior to the publication of ICRP 103, effective dose was calculated using tissue weighting factors taken from ICRP 60, which are different from those in ICRP 103

22.3 MEASURING APPLICATION SPECIFIC QUANTITIES

22.3

22.3 MEASURING APPLICATION SPECIFIC QUANTITIES

22.3

Measuring application specific quantities

22.3.1 General considerations

22.3.2 Measurements using phantoms and patients

22.3.3 Free-in-air measurements

22.3.4 Radiography

22.3.5 Fluoroscopy

22.3.6 Mammography

22.3.7 CT

22.3.8 Dental radiography

22.3 MEASURING APPLICATION SPECIFIC QUANTITIES

22.3.1 GENERAL CONSIDERATIONS

22.3 MEASURING APPLICATION SPECIFIC QUANTITIES

22.3.1 General considerations

Approaches to measurements

- There are two general approaches for the measurements
  - direct measurement on patients or phantoms
  - indirect measurements on patients and phantoms
    - these use free-in-air measurements to characterise X ray output, which are then scaled for exposure and geometry using actual patient or phantom exposure factors
- Detailed in IAEA Report TRS 457
- This report may also be consulted for details of calibration procedures

22.3 MEASURING APPLICATION SPECIFIC QUANTITIES

22.3.1 General considerations

Instruments for measurements

- Application specific quantities can be measured using
  - ionization chambers (including KAP meters) or
  - in some cases, semi-conductor detectors
- For direct patient measurements
  - often choose dosimeters radiolucent in the diagnostic radiology energy range (except mammography)
    - KAP meters or
    - thermoluminescent dosimeters (TLDs)
      - TLDs must be of high sensitivity – able to detect an air kerma of 0.1 mGy
      - it is good practice to construct a TLD dosimeter comprising at least three TLD chips

Instrument calibration (1 of 2)

- In each case, the following equation is used to calculate the relationship between the air-kerma related quantity K and the measurement M

$$K = N_{K,Q_0}\, k_Q M$$

where

- N_{K,Q_0} is the dosimeter calibration at the calibration radiation quality Q_0
- the factor k_Q corrects this to the radiation quality Q of the actual measurement
- the factor k_{TP} corrects for temperature and pressure
  - k_{TP} is unity for semi-conductor dosimeters

Instrument calibration (2 of 2)

- For ionization chambers

$$k_{TP} = \left(\frac{273.2 + T}{273.2 + T_0} \right) \left(\frac{P_0}{P} \right)$$

where

- T and P are temperature and pressure at the time of measurement
- T_0 and P_0 are the corresponding values for the calibration

- Depending on the measurement uncertainty required, use either
  - the normal pressure for the altitude of the measurement and the average temperature in the room of measurement
  - or the actual values at the time of measurement

Measurement uncertainty (1 of 2)

- The measurement uncertainty desirable in the application specific quantities depends upon the use to be made of the measurement
  - the uncertainty of measurement for secondary standard dosimetry laboratories is discussed in IAEA-TECDOC-1585 (2008)
- Report TRS 457 advises, for
  - estimation of absolute stochastic risk: 10%
  - estimation of relative risks (comparative dose measurements): 7%
  - estimation of the dose to the embryo/foetus: 7%
  - quality assurance: 7%

Measurement uncertainty (2 of 2)

- The TRS 457 uncertainties
  - are in addition to any uncertainties in conversion coefficients used for the calculation of risk related quantities
  - all correspond to an expanded uncertainty k=2
  - k=2 corresponds to a 95% confidence limit for the quantity in question
    - see Appendix 1 of IAEA Technical Report TRS 457
- It is important to estimate uncertainties for each measurement
- It is doubtful whether the TRS 457 uncertainties can be achieved in all cases (IAEA 2011)

22.3 MEASURING APPLICATION SPECIFIC QUANTITIES

22.3.2 MEASUREMENTS USING PHANTOMS AND PATIENTS

Advantages of measurements using phantoms

- Measurements using phantoms are useful for:
  - the control of technical parameters, including equipment under automatic exposure control
  - the comparison of the same system at different times
  - the comparison of different systems
  - optimization of individual components of the imaging system or of the whole system

Disadvantages of measurements using phantoms

- Phantom measurements cannot provide
  - a direct estimate of the average dose for a given patient population
  - the variation which occurs in practice because of variations in patient size, and composition
- They also provide no information on how technique factors may vary with the operator
- It is important therefore that measurements made using phantoms are complemented with measurements made on patients, though the measurement frequency will be different for the two types of measurement

Phantoms

- Phantoms vary in degree of complexity and anatomical accuracy
  - generally, the more realistic the more expensive
- If just total attenuation is to be matched, simple plastic phantoms can often be used
  - PMMA phantoms for dosimetry in mammography
  - dosimetry in CT, although in this case, the phantoms cannot be considered to be representative of typical patients
  - simple phantoms designed by the CDRH in the USA
    - available for dosimetry of chest, lumbar spine/abdomen examinations
    - for example, the CDRH abdomen phantom is designed to correspond to an average USA citizen in the antero-posterior projection (average thickness 230 mm)

Patient measurements

- Dosimetric quantities obtained from patient exposures will include
  - variations in equipment performance and operator technique
  - patient-related differences
- So a single measurement will not be representative of clinical practice
  - instead, dosimetric data will need to be collected from a patient cohort so that a median and/or average value can be calculated
- Such values can be used for comparative studies at local, regional, national and international level always provided that the median values of the patient size are similar

Selection of patient cohort

- It is evident that the patient cohort selected must be
  - representative
  - sufficiently large to reduce statistical fluctuations in the median or the average dose for the sample to an acceptable level
- Sample sizes of between 10 and 50 have been used
- Sample median is little influenced by outlying values arising from very large or very small patients
  - if the sample average is to be used, and sample size small, patient selection based on mass can be helpful
- Recording of patient mass and height is always recommended to aid the interpretation of the results

Equipment specific information

- The relationship between risk-related quantities and measured application specific quantities will in general depend upon field size and beam quality
- Information regarding these parameters should be recorded as appropriate

22.3 MEASURING APPLICATION SPECIFIC QUANTITIES

22.3.3 FREE-IN-AIR MEASUREMENTS

Free-in-air measurements

- When the exposure parameters for a radiographic examination are known, the incident air kerma, K_i ,can be calculated directly from
  - the exposure parameters and measurements of the tube output $Y(d)$

$$K_i = Y(d) P_{It}(X) \left[\frac{d}{d_{FSD}} \right]^2$$

where

- d_{FSD} is the focus skin (or phantom surface) distance
- d is the distance from focus to point of measurement of tube output
- P_{It} is the tube loading (mAs) for the exposure

22.3 MEASURING APPLICATION SPECIFIC QUANTITIES

22.3.3 Free-in-air measurements

Tube output measurement

- The dosimeter is placed free-in-air on the central axis of the X ray beam and sufficiently high above the table to reduce the effects of backscatter to a low level
- A solid state dosimeter with shielding from backscatter (lead backing) may instead be placed on the patient table or floor

Note that the dosimeter and control unit are both shown in the photograph for demonstration purposes. In the practical situation, they would be further apart and the cable would not be coiled

Fitting tube output measurements

- Tube output is measured at a range of tube voltages and for the filters in clinical use
- For the purposes of interpolation, the output for each filter can be fitted to

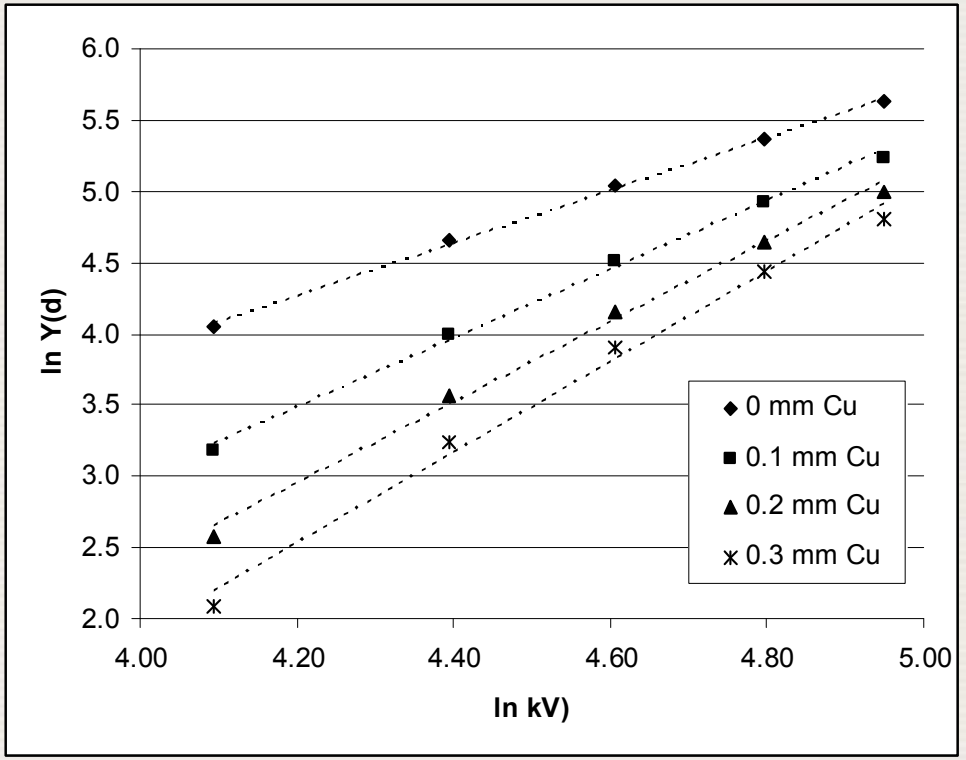
$$Y(d) = a(kV)^n$$

where

- $Y(d)$ is the X ray tube output, kV is the tube voltage, a and n are constants
  - a is specific to the filter in use
  - n has a value of approximately 2 for tungsten targets and 3 for molybdenum targets

Tube output fit

- Variation of tube output with tube voltage for an X ray tube filtered with various thicknesses of copper



22.3 MEASURING APPLICATION SPECIFIC QUANTITIES

22.3.4 RADIOGRAPHY

Measurements in radiography

- The application specific quantities used for dosimetry in radiography are
  - incident air kerma
  - entrance surface kerma
  - air kerma area product

Measurement of air kerma area product in radiography

- In practice, the air kerma area product is the simplest to obtain as long as a calibrated KAP meter is fitted to the X ray tube
  - where this dosimeter is provided by the X ray manufacturer, the reading will usually be displayed on the X ray console
  - occasionally the displayed air kerma-area product is calculated by the X ray generator microprocessor from the exposure factors, the settings of the collimator blades and a generic value for the tube output
- It is therefore important to check the calibration of the KAP meter before using it for patient dosimetry

Measurement of alternative quantities in radiography

- In the absence of a KAP meter
  - incident air kerma or entrance surface air kerma are reasonable alternatives to the air kerma area product
- Both can be most easily obtained using indirect calculation from recorded exposure parameters
  - direct measurement is also possible
- For entrance surface air kerma, direct measurements may be preferred, as these will include backscatter
  - the dosimeter is placed on the entrance surface of the patient or phantom at the centre of the X ray field and the exposure is taken in accordance with normal clinical practice

22.3 MEASURING APPLICATION SPECIFIC QUANTITIES

22.3.5 FLUOROSCOPY

Measurements in fluoroscopy

- Fluoroscopic examinations are by their nature very variable
  - changes in mode (i.e. fluoroscopy, image acquisition), exposure factors, filtration, projection, collimation and body part irradiated may all take place during such examinations
- The patient dose will depend on the size of the patient, the operator selections and the complexity of the case
  - dosimetric quantities based on patient exposures are essential
- Phantom exposures are of use for simple procedures and for quality control to ensure suitable setup and optimization of the equipment

Quantities measured in fluoroscopy

- The air kerma-area product is the dosimetric quantity of choice for the estimation of radiological risk
  - because of this variability
- The use of incident air kerma and entrance surface air kerma is however, needed for examinations where there is a risk of
  - skin injury
  - exposure of the eye to unattenuated beam

Measurements of air kerma-area product in fluoroscopy

- For fluoroscopy systems the total air kerma-area product for the examination and the total fluoroscopy time are displayed on the X ray console
  - the total air kerma-area product is usually measured with a KAP meter but can also be calculated
    - note the caveat in the previous section on checking calibration
- In the case of under couch units
  - the measured air kerma-area product overestimates the air kerma-area product to the patient due to attenuation of the X ray beam by the patient couch
  - accurate correction for couch attenuation is often not practical as it is a function of beam quality and X ray projection

Measurements of incident air kerma in fluoroscopy

- Modern interventional fluoroscopy units will report the incident air kerma at a reference point calculated from the air kerma-area product, the collimator settings, and the exposure geometry
- The reported incident air kerma can be used to estimate the maximum value of the entrance surface area kerma
  - this is the maximum value because changes in projection angle during the examination have been ignored
  - this may be a useful quantity for monitoring skin dose, but must be fully understood and calibrated before being used in patient dose surveys

Entrance surface air kerma measurements

- Measurements of entrance surface air kerma rates on phantoms for
  - selected clinical protocols
  - typical projections
- Combine with fluoroscopy times, image acquisition parameters and selected field sizes to yield an estimate of the total entrance surface air kerma for simple examinations

Note that the dosimeter and control unit are both shown in the photograph for demonstration purposes. In the practical situation, they would be further apart and the cable would not be coiled

Measurement of entrance surface air kerma using PMMA slab

22.3 MEASURING APPLICATION SPECIFIC QUANTITIES

22.3.6 MAMMOGRAPHY

Measurements in mammography

- The application specific quantities appropriate for dosimetry in mammography are
  - incident air kerma
  - entrance surface air kerma
- Incident air kerma is required for the calculation of mean glandular dose
- Entrance surface air kerma is little measured or used

Measurements of incident air kerma in mammography

- The standard method of determining the incident air kerma, Ki, for both patient and phantom exposures is to calculate it using (see section 22.3.3)

$$K_i = Y(d) P_{It}(X) \left[\frac{d}{d_{FSD}} \right]^2$$

and

- measurements of tube output
- knowledge of the exposure parameters used for the examination (tube charge (mAs), tube voltage and filtration and breast or phantom thickness)

- Direct measurements are little used for dosimetry with phantoms
- Direct measurements are not possible for patient exposures because of the visibility of even small dosimeters such as TLD on the image

Measurements using phantoms in mammography

- Measurements using PMMA phantoms are included in national quality control programmes for mammography
  - patient measurements are needed to determine the actual distributions of mean glandular dose
- Unlike for many situations in radiography and fluoroscopy, the standard phantoms are well defined for mammography, so that comparisons between different sites at national and international level are feasible

22.3 MEASURING APPLICATION SPECIFIC QUANTITIES

22.3.7 CT

Measurements in CT

- The application specific dosimetric quantities that can be used for patient dosimetry in CT are
  - the free-in-air CT kerma index, $C_{a,100}$
  - the in-phantom CT kerma indices, $C_{PMMA,100,p}$ and $C_{PMMA,100,c}$
  - the weighted CT kerma index, C_W
  - the volumetric CT kerma index, C_{VOL}
  - the kerma length product, $P_{KL,CT}$

Measurement of free-in-air and in-phantom kerma indices

- Use
  - pencil ionization chamber
    - preferred option for practical reasons
  - or stack of TLDs
- The standard active length of the chamber is 100 mm to match the integration limits for the CT kerma indices measured free-in-air, or in-phantom
- In general the measured indices are normalized by the exposure time- tube current product (mAs) and can be scaled where necessary to match the exposure parameters for a given procedure

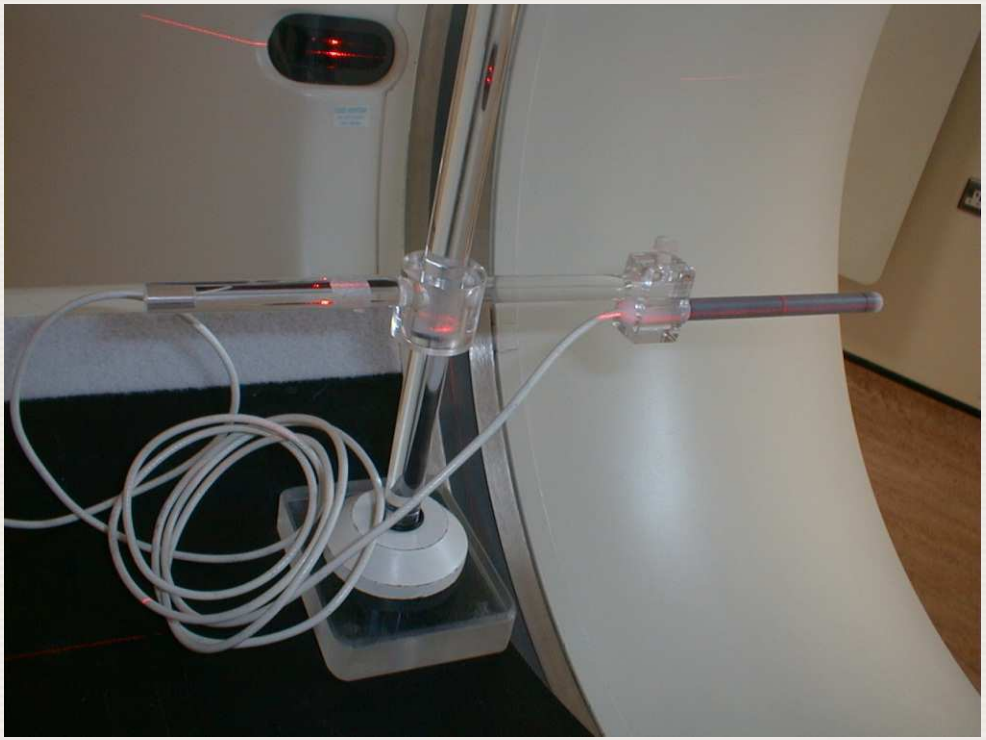
Measurement of free-in-air kerma index in CT

- The free-in-air CT kerma index is useful for
  - characterising the tube output of the CT scanner
  - quality control
- The free-in-air CT kerma index is
  - easy to measure by aligning the pencil chamber with the scanner axis of rotation
  - not influenced by the shaped beam filtration which is present in the scanner
  - also required as a scaling factor when using some tabulated conversion factors to calculate absorbed organ doses or effective dose

22.3 MEASURING APPLICATION SPECIFIC QUANTITIES
22.3.7 CT

Measurement of the CT air kerma index free-in air, $C_{a,100}$

- The chamber is clamped in a specially designed support and aligned so that it is coaxial with the scanner rotation axis and its sensitive volume is bisected by the scan plane
- In this particular example, alignment has been achieved with the aid of laser lights



The cable is shown coiled in the demonstration photograph, but in the real practical situation, it would not be coiled

Measurement using phantoms in CT

- In-phantom measurements give a better measure of patient dose
- The weighted CT kerma index provides an estimate of the average dose within a slice for a single scanner rotation without translation
  - obtained by combining together measurements of $C_{PMMA,100}$ in the centre and peripheral positions of a standard CT dosimetry phantom
- Two phantoms are used
  - standard head phantom
  - standard body phantom

Standard phantoms in CT

- Standard head and body phantoms
  - circular cylinders constructed from PMMA
  - have bores at the centre and at the cardinal points 1 cm below the surface to facilitate measurement
  - diameters are 16 cm and 32 cm

Measurement of the CT air kerma index, $C_{PMMA,100,c}$ in the standard body phantom

- The body phantom is positioned on the couch top
  - note that standard head phantom forms the inner portion of the body phantom
- The chamber is positioned in the central hole of the phantom
- A plastic sleeve is placed over the chamber to ensure a good fit within the phantom
- The central plane of the phantom has still to be aligned with the position of the scan slice

The cable is shown coiled in the demonstration photograph, but in the real practical situation, it would not be coiled

Measurement of weighted CT kerma index

- The weighted CT kerma index is useful for characterising the dosimetric performance of the CT scanner, but not for patient dosimetry as it applies to a single scan rotation, not the whole scan
- Once measured it can be used to calculate the volumetric CT kerma index and hence the air kerma length product
  - using the pitch and tube loading
- These can be considered to be the preferred quantities for patient dosimetry in CT)
  - but must be used with care

Phantom and patient exposures in CT

- Patient dosimetry in CT is unique in diagnostic radiology in that the CT-specific dosimetric quantities are defined in terms of standard phantoms, yet are applied to patient exposures
  - the size of the patient may be different from the size of the phantom
  - dosimetric quantities may over- or under-estimate the air kerma in the patient
- The volumetric CT kerma index and the air kerma length product cannot be measured on a patient in the way that incident air kerma, air kerma area product etc can be
- It is therefore vital to remember that in CT dosimetric quantities refer to phantoms

Measurement of volumetric CT kerma index

- Modern CT scanners report the volumetric CT kerma index on the scanner console; it is shown as the "$CTDI_{vol}$"
- It is more convenient to record this displayed value than to calculate it from measurements of weighted CT kerma index and the scan parameters
  - in the case of CT scanners with tube current modulation, the average volumetric CT kerma index for the scan can realistically be obtained from the display alone
  - this approach is acceptable if the volumetric CT kerma index calculation has been validated against measurement

Measurement of air kerma length product in CT

- Modern CT scanners also report the air kerma length product on the scanner console
  - it is shown as the 'DLP'
- This approach is also acceptable if the DLP calculation has been validated against measurement

22.3 MEASURING APPLICATION SPECIFIC QUANTITIES

22.3.8 DENTAL RADIOGRAPHY

Measurements in dental radiography

- Dosimetric measurements are normally made based on patient exposures rather then using phantoms
- The dosimetric quantities generally used are
  - the incident air kerma, which is readily measured for intraoral examinations
  - the kerma length product and kerma area product which are used for panoramic examinations

Measurements of exposure in dental radiography

- On dental radiography equipment exposures are generally set manually by the operator, or selected from default protocols
  - the exposure factors are therefore not dependent on the subject
- In the case of panoramic units which use automatic exposure control
  - typical exposure parameters must be recorded so that the exposure can be duplicated under manual control for dosimetry purposes
- Direct measurements are preferred in dental radiography as they are easy to implement
  - the number of protocols used clinically is generally small, so measurements for each protocol are more time-efficient than characterising the tube output

Measurements of incident air kerma in intraoral dental radiography

- For intraoral examinations the incident air kerma may be measured by placing the dosimeter
  - free-in-air
  - at the end of the spacer / alignment cone
  - in the centre of the X ray beam
- The exposure is taken using a standard clinical protocol

Measurements of air kerma length product in panoramic dental radiography

- For panoramic dentistry, the air kerma length product can be measured using
  - a cylindrical ionization chamber or
  - a stack of TLDs which are longer than the width of the X ray beam
- The ionization chamber is most easily affixed to the detector housing across the centre of the secondary X ray beam slit and the exposure taken using a standard clinical protocol
- The air kerma area product can be estimated from the air kerma length product by multiplying by the height of the X ray beam at the position of the dosimeter
  - this height can be measured using an X ray film or a computed radiography plate

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4

Estimating Risk Related Quantities

- It was noted previously that the absorbed dose to individual organs and tissues has to be quantified in order to assess radiation detriment
- Because of the difficulty of direct measurement, organ or tissue dose is generally estimated from
  - a measurement (or calculation) of an application specific quantity (such as incident air kerma or air kerma-area product)
  - an absorbed dose conversion coefficient, *c*, defined as

$$c = \frac{organ\ or\ tissue\ dose}{measured\ or\ calculated\ quantity}$$

Absorbed dose conversion coefficients

- Suffices are added to c to denote the particular quantities used
- For example to relate incident air kerma K_i to organ dose D_T, we use

$$c_{D_T,K_i} = \frac{D_T}{K_i}$$

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.1 DETERMINATION OF ORGAN DOSE CONVERSION COEFFICIENTS

Estimating Risk Related Quantities

- 22.4.1 Determination of organ dose conversion coefficients
  - Monte Carlo Methods
  - Phantom Measurements
- 22.4.2 Backscatter factors
- 22.4.3 Use of data

Monte Carlo Methods

- The key features of a Monte Carlo model for the calculation of absorbed dose conversion coefficients are
  - simulation of the radiation field incident on the patient (including field size, direction and X ray spectrum)
  - simulation of photon transport through the patient
  - simulation of the patient
- Once such a program has been developed, it is used to simulate a wide range of examinations and X ray spectra
  - Monte Carlo methods are generally a much more powerful tool for the production of tables of conversion coefficients than measurements using anthropomorphic phantoms

Monte Carlo simulation of photon histories

- The methodology for the simulation of photon histories is well established
- For the diagnostic energy range, it is sufficient in most cases to assume that energy deposited after a photon interaction is locally absorbed
  - so that organ doses may be estimated by recording the energy depositions that take place when many photons histories are followed
- An important exception to this is the energy deposition in the red bone marrow
  - the range of secondary electrons may be comparable to the size of the marrow cavities and electron transport must then be considered
  - a correction may be applied for this effect

Monte Carlo simulation of human body

- Two approaches have been adopted for the simulation of the human body
  - use a mathematical phantom (also known as a geometrical phantom)
  - use one or more voxel phantoms based on the anatomy of individuals

Monte Carlo simulation with mathematical phantoms

- The body and the organs it contains are constructed as combinations of various geometrical solids
- The first such phantom was based on the ICRP Reference Man of 1975
- A series of other phantoms have subsequently been developed which represent for example children (neonate and 1, 5, 10 and 15 years old) and adult males and females
- Mathematical phantoms can be criticized as being unrealistic in terms of organ position and shape

Monte Carlo simulation with voxel phantoms

- An alternative and more realistic approach is to use one or more voxel phantoms based on the anatomy of individuals
- Such phantoms may be obtained, for example, from whole body CT or MRI images, which have been segmented voxel by voxel into different organs and tissue types

Statistical errors in Monte Carlo methods

- As a result of the statistical nature of Monte Carlo simulations, the organ dose conversion coefficients have associated statistical errors
- In general, the statistical uncertainties in the doses to organs lying within the radiation field will be less than those for organs lying outside the radiation field
- For organs lying outside the radiation field, the relative uncertainty will increase with the distance from the edge of the field

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.1 Determination of organ dose conversion coefficients

Tables of organ dose conversion coefficients

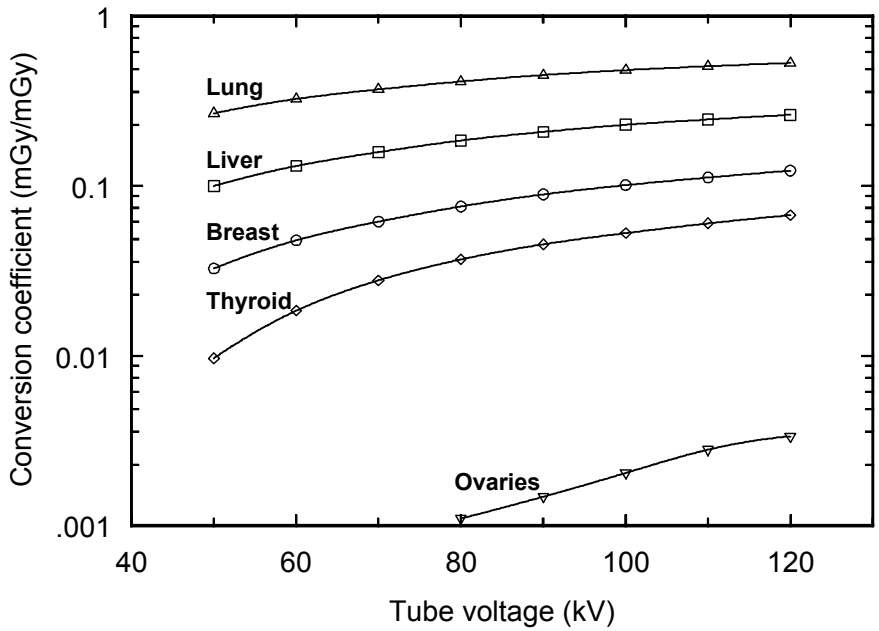
- Organ dose conversion coefficients calculated using Monte Carlo techniques have been published by various authors
  - the most extensive tabulations are those of the Center for Devices and Radiological Health (CDRH) in the USA, the GSF in Germany and the National Radiological Protection Board (NRPB) in the UK
- The choice of tabulation for a particular situation will depend upon
  - data availability
  - how well the situation modelled (including the radiation field parameters and the patient or patient population) matches the situation for which the organ doses are required

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.1 Determination of organ dose conversion coefficients

Organ dose conversion coefficients and beam quality

- All conversion coefficients are beam quality dependent
- In most situations it is adequate to linearly interpolate between values of the conversion coefficients at different beam qualities
- The figure shows variation with tube voltage of organ dose conversion coefficients for several tissues, for a chest postero-anterior examination. X ray spectra have total filtration of 3 mm Al.



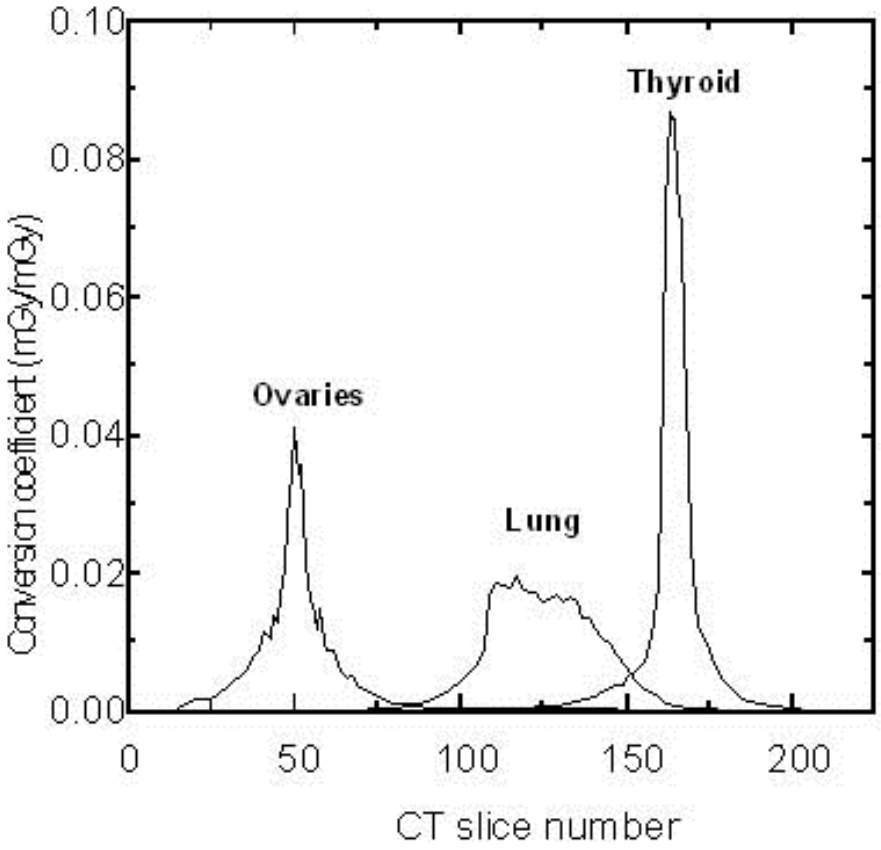
Data taken from Hart D, Jones D G, and Wall B F, Normalized organ doses for medical X ray examinations calculated using Monte Carlo techniques. Report NRPB-SR262, National Radiological Protection Board (Chilton, UK) 1994

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.1 Determination of organ dose conversion coefficients

Organ dose conversion coefficients in CT

- For CT it is important to match the data to the particular scanner used
- The figure shows how the conversion coefficient for absorbed dose to the lungs, thyroid and ovaries varies with CT slice position
  - for a particular CT scanner
  - for single CT slices 5 mm thick



Data based on Jones D G and Shrimpton P C, Normalized organ doses for X ray computed tomography calculated using Monte Carlo techniques, Report NRPB SR250, National Radiological Protection Board (Chilton UK), 1991

Phantom measurements

- For situations where no appropriate Monte Carlo-calculated conversion coefficients are available, it may be necessary to make custom measurements of organ dose using a suitable anthropomorphic phantom
- The measurement of local skin dose for a fixed radiation field is quite straightforward
  - providing that the incident air kerma varies slowly across the field

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.1 Determination of organ dose conversion coefficients

Phantom measurements of organ dose

- For the measurement of organ dose for internal organs TL-dosimeters are often used
- There are two effects that make such measurements difficult
  - the rapid decrease of dose with depth in tissue
  - the partial irradiation of some organs by the primary beam
- Particularly difficult to obtain adequate spatial sampling for
  - large organs (such as lungs)
  - widely distributed tissues (such as red bone marrow)

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.2 BACKSCATTER FACTORS

Estimating Risk Related Quantities

- 22.4.1 Determination of organ dose conversion coefficients
- 22.4.2 Backscatter factors
- 22.4.3 Use of data

Backscatter factors

- The backscatter factor B relates the incident air kerma K_i and entrance surface air kerma K_e in accordance with

$$K_e = K_i B$$

- It is necessary to convert from incident air kerma to entrance surface air kerma or vice versa, when
  - organ dose conversion coefficients are available normalized to incident air kerma, but only measurements of entrance surface air kerma are available
  - measurements of the two air kerma quantities need to be compared
  - the incident air kerma is known and local skin dose has to be estimated (sometimes very important)

Determination of backscatter factors

- Like organ dose conversion coefficients, backscatter factors can be calculated
  - using Monte Carlo methods or
  - measured using a suitable phantom (to provide backscatter)
- The backscatter factor depends on field size and beam quality

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.2 Backscatter factors

Tube Voltage	Filtration	Backscatter factor B, for water	
(kV)	(mm Al)	100x100 mm^2 field	250x250 mm^2 field
50	2.5	1.24	1.26
100	3.0	1.36	1.45
150	3.0	1.39	1.52

Data taken from Petoussi-Hens N, Zankl M, Drexler G, Panzer W and Regulla D, Calculation of backscatter factors for diagnostic radiology using Monte Carlo methods. Phys. Med. Biol. 43 (1998) 2237-2250

Effect of backscatter material

- The effect of backscatter material is also significant
- For a 150 kV spectrum filtered by 3mm of aluminium and a 250x250 mm^2 field
  - the values of B for water, ICRU tissue and PMMA backscatter materials are: 1.52, 1.53 and 1.63 respectively
  - this shows that PMMA is not a good tissue substitute material in this case

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.3 USE OF DATA

Estimating Risk Related Quantities

- 22.4.1 Determination of organ dose conversion coefficients
- 22.4.2 Backscatter factors
- 22.4.3 Use of data
  - Radiography and fluoroscopy
  - Mammography
  - CT
  - Dental Radiography
  - Foetal dose calculations

Use of data

- To estimate risk related quantities such as organ dose and effective dose for a given examination and patient size
  - appropriate conversion coefficients (c) are selected from tabulated data by matching the projection, radiation field and beam quality of the examination
  - the selected conversion coefficient is then multiplied by the value of the application-specific quantity (say Q_i) measured for the examination

$$D_T = Q_i \, c_{D_T, Q_i}$$

Use of data – model selection

- It is important to note that it may not be possible to get a good match between
  - the size of the modelled patient
  - the position and size of the modelled organs and
  - the position and size of the radiation field and those of the real situation
- Significant errors can arise as a consequence
- Whole organs may lie
  - wholly within or partly within the field for one case
  - wholly outside the field for the other
  - and their depth within the body can be quite different

Use of data – differences in organ dose conversion coefficients for different phantoms

- The table (next slide) demonstrates the differences in organ dose conversion coefficients
- For a posterior-anterior chest examination
  - at 141 kV, total filtration: 5.7 mm Al, focus image distance: 1500 mm, field size at the image plane: 350 mm x 400 mm
- Three different phantoms that simulate an adult male are used
  - ADAM mathematical phantom
  - GOLEM voxel phantom
  - VISIBLE HUMAN voxel phantom

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.3 Use of Data

Organ	Organ dose per unit incident air kerma (mGy/(mGy)		
	Voxel Golem	Voxel Visible Human	Mathematical Adam
Colon	0.09	0.04	0.008
Testes	–	–	–
Liver	0.38	0.30	0.27
Lungs	0.57	0.51	0.79
Pancreas	0.27	0.19	0.32
Red bone marrow	0.26	0.21	0.21
Skeleton	0.40	0.33	0.39
Spleen	0.77	0.52	0.39
Small intestine	0.09	0.04	0.01
Stomach wall	0.30	0.24	0.14
Thyroid	0.28	0.18	0.14
Surface (entrance)	1.27	1.40	1.39
Surface (exit)	0.10	0.07	0.09

Data taken from Petoussi-Henss N, Zankl M, Drexler G and Panzer, W. Phys Med Biol. 43 (1998) 2237-2250

Use of data – available phantoms

- The ADAM mathematical phantom and GOLEM voxel phantom have
  - similar external dimensions
  - but the coefficients for several organs including lung, liver and thyroid are significantly different, due to differences in the size, shape and position of the internal structures for the two phantoms
- The VISIBLE HUMAN voxel phantom is much larger than the GOLEM phantom
  - the conversion coefficients in general decrease with increasing patient size, due to the increased shielding offered to most organs as the body size increases

Radiography and fluoroscopy – conversion coefficients

- Conversion coefficients for radiography and fluoroscopy are available
  - normalised to kerma area product, incident air kerma and entrance surface air kerma
- Software is available for some of the data tabulations
  - can greatly facilitate the calculation of organ or effective dose
- A PC-based Monte Carlo computer program (PCXMC)
  - from the Radiation and Nuclear Safety Authority (STUK) in Finland
  - can directly compute organ doses for user specified radiation fields, with the added feature of adjusting the size of the patient, including sizes appropriate for paediatric dosimetry

Radiography and fluoroscopy – large X ray fields

- A potential source of further error is the use of the air kerma area product in situations where the X ray field extends beyond the patient
- A useful check on the accuracy of the calculation is
  - to estimate the incident air kerma from the air kerma area product with knowledge of the X ray beam area
  - repeat the calculation of organ or effective dose using the estimated incident air kerma

Radiography and fluoroscopy – paediatric dosimetry

- In the case of paediatric dosimetry it is unlikely that the subjects will match the paediatric phantoms used to calculate existing tables of conversion coefficients
- This problem can be avoided by using PCXMC
- Alternatively, tabulated conversion coefficients can be plotted against a measure of phantom size – not age – and the conversion coefficient appropriate for the size of the subject deduced by interpolation

Mammography

- Different approaches have been adopted for patient dosimetry in mammography in Europe and the USA and the methodology is still developing
- The methodology in Technical Report TRS 457 followed European practice at that time and is outlined here
- The same general approach is also used in the more recent IAEA report on quality assurance for screen film mammography (IAEA Human Health Series Report 2)

Patient dosimetry in mammography in Europe

- The mean glandular dose (MGD), D_G, for a patient examination is calculated for full field contact mammography using

$$D_G = g\,c\,s\,K_i$$

where

- K_i is the incident air kerma for the patient exposure
- g is the conversion coefficient from incident air kerma to mean glandular dose for a standard breast of 50 % glandularity
- c corrects for differences in glandularity between the patient breast and the standard breast
- s corrects for differences in the spectrum used

- The factors g and c depend on the beam quality used to image the breast and are tabulated as function of HVL

Patient dosimetry in mammography in Europe – breast model

- The standard breast model used for the Monte Carlo simulations
  - was semi-circular in cross section
  - of radius 80 mm
  - with a central region comprising a uniform mixture of adipose and glandular tissues
- Such a model is clearly not representative of all breasts, but provides a reasonable indication of a typical dose for a breast of a given glandularity
- The same tables of factors are used for cranio-caudal and oblique projections

Patient dosimetry in mammography in Europe – glandularity

- It is necessary to know the glandularity of the breast in order to apply

$$D_G = g\,c\,s\,K_i$$

- Glandularity will in general not be known and typical values can be used instead where these are available
- Such data are available from a number of countries
- Table shows the equivalence between typical breasts and PMMA phantoms for women aged 50-64 attending for breast screening in the UK

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.3 Use of data

PMMA thickness mm	Equivalent breast thickness mm	Equivalent breast glandularity %
20	2.1	97
30	3.2	67
40	4.5	40
45	5.3	29
50	6.0	20
60	7.5	9
70	9.0	4
80	103	3

Data taken from Dance et al, Phy. Med. Biol 45 (2000) 3225-3240

Patient dosimetry in mammography in Europe – phantoms

- Dosimetry using phantoms is much used in mammography
- PMMA is a suitable tissue substitute and TRS 457 uses a standard phantom 45 mm thick to simulate a breast 50 mm thick of 50 % glandularity
  - because the equivalence is not exact, a small correction term is included in the conversion coefficient used
- In the IAEA report on quality assurance for screen film mammography, this phantom is used to simulate a standard breast 53 mm thick and 29% glandularity
  - in this case the equivalence between the phantom and the standard breast is exact

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.3 Use of data

Patient dosimetry in mammography in Europe – alternative approach

- An alternative approach, which avoids the use of the small correction term, is to find the typical breast which gives the same incident air kerma as a given thickness of PMMA
- The resulting thicknesses and compositions are given in the table for women aged 50-64 attending for breast screening in the UK
- The expression $D_G = g\,c\,s\,K_i$ can then be used directly

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.3 Use of data

PMMA thickness mm	Equivalent breast thickness mm	Equivalent breast glandularity %
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80	103	3

Data taken from Dance et al, Phy. Med. Biol 45 (2000) 3225-3240

Patient dosimetry in mammography – additional points

- For magnification mammography, the MGD can be approximated by calculating in accordance with

$$D_G = g\,c\,s\,K_i$$

  - the result is then scaled by the ratio of the breast area directly irradiated to that of the compressed breast
- Very occasionally effective dose is required
  - it is reasonable to assume that the absorbed radiation dose in other organs is negligible
  - the organ weighting factor for the breast must be doubled when calculating effective dose for a woman, as it is based on the average risk for men and women

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.3 Use of data

CT

- Monte Carlo conversion factors for CT are fundamentally different from those available for projection radiology because
  - they are tabulated for a sequence of contiguous transverse slices through the phantom
  - rather than per CT examination
- The most widely used Monte Carlo data for CT are the conversion coefficients available from
  - NRPB (National Radiation Protection Board (UK))
  - GSF (National Research Centre for Environment and Health (Germany))

22.4 ESTIMATING RISK RELATED QUANTITIES

22.4.3 Use of data

Source of tabulated conversion factors	Phantom	Data sets	Application specific quantity	Risk related quantity
NRPB	Adult Cristy	23	CT kerma index for ICRU muscle	Organ dose
GSF	Adam, Eva, Child, Baby	3	$C_{a,100}$	Organ dose

CT dosimetry software

- The practical use of these tabulations is greatly facilitated by software which can integrate the conversion coefficients for individual slices to obtain organ doses for a complete scan
  - the ImPACT CT Patient Dosimetry Calculator is commonly used to manipulate the NRPB data sets
  - CT-Expo is based on the GSF data sets

CT dosimetry – correction for scanner used

- Note that the NRPB and GSF calculations were reported in 1993 and 1991 respectively using scanners that are no longer in use
- Due to the large diversity of scanner types and their continual change it is necessary to utilize scanner correction factors as well as conversion coefficients to accurately estimate organ dose for CT
- Extensive work to establish a basis for these factors has been carried out by ImPACT
- Third party providers of CT dose calculators have incorporated these scanner correction factors into their calculation algorithms
  - but their use is not always readily apparent

CT dosimetry – potential pitfalls with third party CT dose calculators

- Setting the scan range
  - radiosensitive organs should be covered to the same extent as in the patient exam
  - the range should include overscanning in spiral mode
- Scan mAs
  - in spiral mode the scan mAs can be the actual mAs or the equivalent mAs for a pitch of 1 depending on the manufacturer
- Tube current modulation
  - the average mAs for the CT scan can be used without incurring significant errors

CT dosimetry – paediatric patients

- Organ and effective doses for paediatric patients can be estimated by
  - calculating the dose for the Eva, Child and Baby phantoms
  - plotting the results against patient weight, establishing the best-fit function
  - calculating the organ or effective dose at the appropriate weight

CT dosimetry – Effective dose

- An approximate relationship between kerma length product and effective dose calculated has been established using the NRPB CT conversion factors
- This empirical relationship facilitates a rough estimate of effective dose directly from $P_{KL,CT}$

$$E = C_{E,KLP} P_{KL,CT}$$

where

- E is the effective dose
- $C_{E,KLP}$ is a conversion factor which is specific to phantom size, anatomical site and is broadly independent of CT scanner model
- values of $C_{E,KLP}$ from Shrimpton (2005) and AAPM (2008)

Dental radiography

- The radiation risk associated with dental radiography is very small, so the calculation of organ dose or effective dose is not carried out routinely
- Therefore no extensive tabulations of conversion coefficients exist for dental radiography

Foetal dose calculations

- From time to time it is necessary to estimate the foetal dose for a given exam, e.g. when the foetus was in the primary beam
- For a gestational age between 0 and 12 weeks
  - the dose to the uterus can be used as a surrogate for foetal dose
- For gestational ages greater than 12 weeks
  - appropriate conversion coefficients should be used but only limited data are available

22.5 DOSE MANAGEMENT

22.5 DOSE MANAGEMENT

Dose Management

- The ICRP recommends in publication 105 that it is not appropriate to set dose limits or dose constraints for patient exposures
  - because the medical condition is invariably more significant than the potential for radiation harm arising from any justified exposure
- Instead the ICRP recommends that justification and dose optimization are the primary tools for radiological protection of the patient
  - dose management is implicit in the optimization task
- Patient doses can be successfully managed only
  - if information is available on the magnitude and range of doses encountered in clinical practice
  - and diagnostic reference levels (DRLs) are set using this data
- Local practice can then be improved by comparison with appropriate DRLs

22.5 DOSE MANAGEMENT

22.5.1 POPULATION-BASED DOSE SURVEYS

Dose Management

- 22.5.1 Population-based dose surveys
- 22.5.2 Diagnostic reference levels
- 22.5.3 Local dose audit

Population-based dose surveys

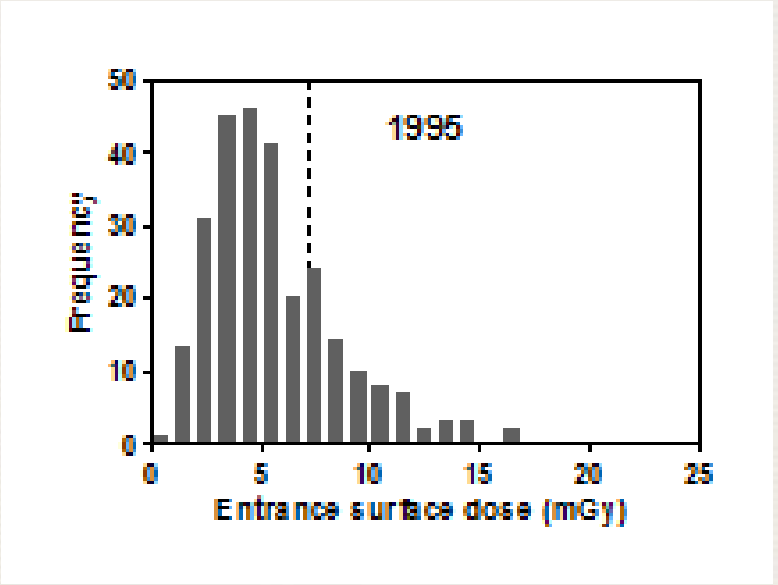
- A number of countries have rolling programmes of patient dose surveys for common X ray and CT examinations, such as the
  - nationwide Evaluation of X ray Trends (NEXT) programme in the US
  - five-yearly reviews of the UK national patient dose data base
- Their findings are published on their websites and as scientific papers
- Several other countries conduct *ad hoc* patient dose surveys, the results of which can be found in the scientific literature
- A variety of methodologies (e.g. patient measurements, phantom measurements) and dose quantities (e.g. entrance surface air kerma, incident air kerma) are reported, so care must be exercised when undertaking comparisons

22.5 DOSE MANAGEMENT

22.5.1 Population-based dose surveys

The UK distribution of X ray room mean entrance surface doses for the AP abdomen examination reported in 1995

- The shape of the distribution is typical of patient dose surveys: A broad, skewed distribution with a high dose tail
- The mean entrance surface dose for this examination is 5.6 mGy, but the doses range between 0.75 and 16.6 mGy, and the ratio of the third to the first quartile is 2.0
- The range in doses encountered can be in part explained by the differences in screen/film systems in clinical use, which ranged in ISO speed from less than 200 to more than 600



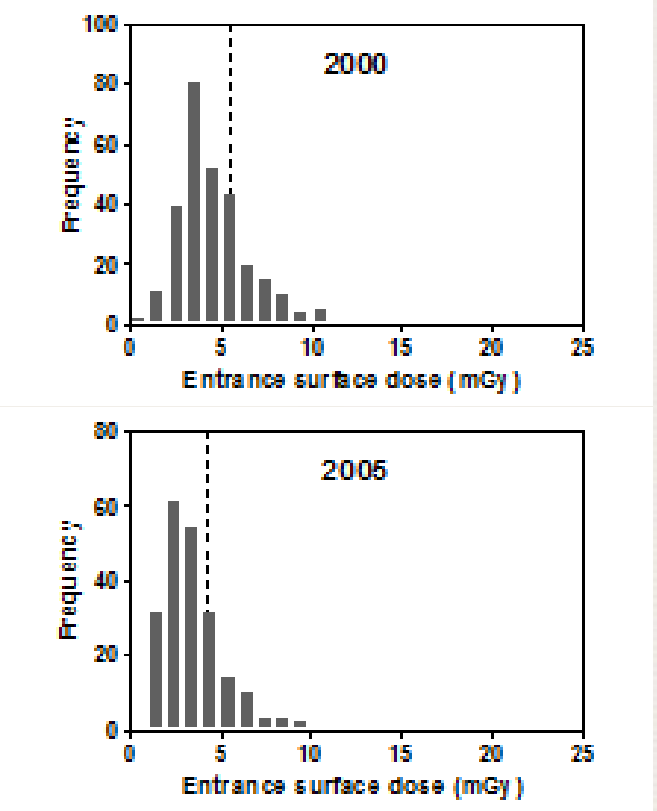
Data from: Hart D, Hillier M C, Wall B F, Doses to patients from radiographic and fluoroscopic X ray imaging procedures in the UK – 2005 review, Report HPA-RPD-029, Health Protection Agency (Chilton UK), 2007

22.5 DOSE MANAGEMENT

22.5.1 Population-based dose surveys

Comparison of the distributions of the X ray room mean entrance surface doses in the UK for AP abdomen in 2000 and 2005 (1 of 2)

- The dotted lines show the national reference dose set at the third quartile of the distribution
- A downward trend in the mean entrance surface dose and the national reference dose is evident over time
- This was achieved by improvements in film/screen speed: in the 1995 survey 40 % of the rooms used ISO speeds lower than 400, in 2005 this figure was 13 %



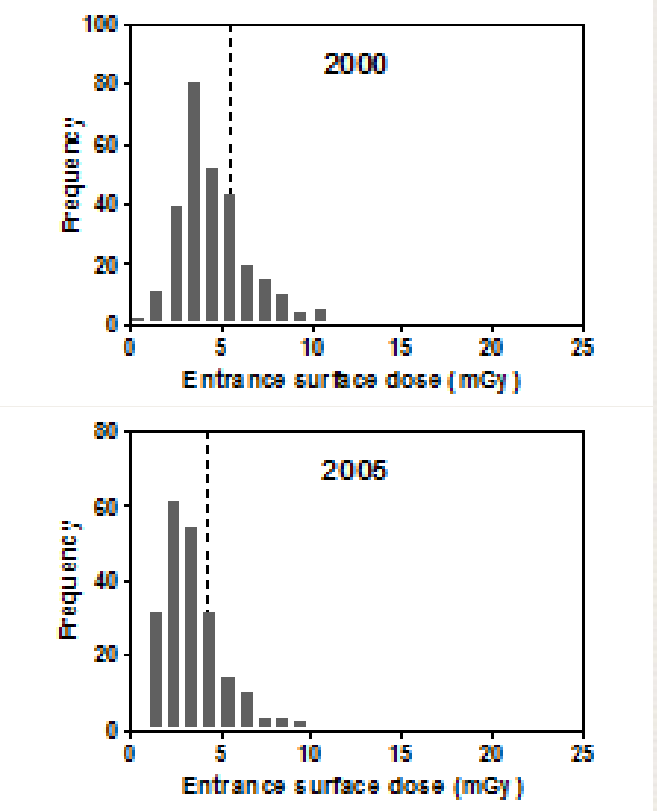
Data from: Hart D, Hillier M C, Wall B F, Doses to patients from radiographic and fluoroscopic X ray imaging procedures in the UK – 2005 review, Report HPA-RPD-029, Health Protection Agency (Chilton UK), 2007

22.5 DOSE MANAGEMENT

22.5.1 Population-based dose surveys

Comparison of the distributions of the X ray room mean entrance surface doses (2 of 2)

- The high dose tail is less prolonged in 2005 than 1995, providing evidence that national reference doses work as a dose management tool by encouraging outliers to review their practices
- Nevertheless some X ray rooms still exceeded the 1995 national reference dose in 2005
- The ratio of the third quartile to the first quartile does not change with time, suggesting that dose optimisation (which would result in a narrowing of the dose distribution) is not taking place, or is less influential than the range in detector technology



Data from: Hart D, Hillier M C, Wall B F, Doses to patients from radiographic and fluoroscopic X ray imaging procedures in the UK – 2005 review, Report HPA-RPD-029, Health Protection Agency (Chilton UK), 2007

22.5 DOSE MANAGEMENT

22.5.2 DIAGNOSTIC REFERENCE LEVELS

Dose Management

- 22.5.1 Population-based dose surveys
- 22.5.2 Diagnostic reference levels
- 22.5.3 Local dose audit

Diagnostic reference levels

- The ICRP identify diagnostic reference levels (DRLs) as an essential tool in the management of patient dose
- DRLs provide the means of deciding whether the typical patient dose for a particular medical imaging procedure is too high or too low
- Note that DRLs are not intended for the management of individual patient doses
- In some countries, for example members of the European Union, DRLs are required by law

Obtaining diagnostic reference levels

- DRLs are obtained from
  - patient dose surveys or
  - exposures of standard phantoms
- DRLs obtained from patient dose surveys apply to standard patients only, e.g. 70 kg for an adult in some countries
- DRLs are most useful for dose management if they are set in terms of application specific quantities because they will then match the data available from dose surveys

Diagnostic reference levels and application specific quantities

- For simple X ray exams, e.g. where the tube voltage does not vary, a single exposure factor such as the tube current exposure time product may be sufficient as the DRL
- CR and DR systems display an exposure index
  - the exact quantity is manufacturer-dependent
  - these exposure indices refer to irradiation of the detector, not the patient, and correlate poorly with patient dose because of susceptibility to other variables such as anatomical region and collimation
  - they are therefore not useful for patient dose management

Setting diagnostic reference levels

- DRLs can be set at international, national, regional and local levels
- In many countries, national DRLs are set for common X ray and CT examinations at the 75 % centile of the national patient dose distributions
- Examples follow:
  - Sweden's DRLs for common adult X ray exams
  - Austria's DRLs for a selection of common paediatric exams
  - UK's DRLs for a selection of adult CT exams
  - UK's DRLs for a selection of paediatric CT exams

Sweden's DRLs for common adult x ray exams

Examination	DRL	Quantity
Chest	0.6 Gy cm^2	KAP
Coronary angiography	80 Gy cm^2	KAP
Barium enema	50 Gy cm^2	KAP
Urography	20 Gy cm^2	KAP
Lumbar spine	10 Gy cm^2	KAP
Pelvis, Hip joints(AP or PA view)	4 Gy cm^2	KAP
Mammography (complete examination)	4 mGy	MGD

Data from: The Swedish Radiation Protection Authority's Regulations and General Advice on Diagnostic Standard Doses and Reference Levels within Medical X ray Diagnostics (SSIMFS 2008:20), 2008

Austria's DRLs for common paediatric X ray exams

Examination	Age	Incident air kerma (μGy)	KAP (μGy m²)
Chest AP/PA	0	50	1.7
	1 y	60	2.3
	5 y	70	2.6
	10 y	90	3.7
	15 y	110	7.3
skull AP/PA	0	350	15
	1 y	600	25
	5 y	750	35
	10 y	900	45
	15 y	1000	50

BILLINGER, J., NOWOTNY, R., HOMOLKA, P., Diagnostic reference levels in pediatric radiology in Austria, Eur Radiol 20 7 (2010) 1572-9

Reference doses recommended for use as DRLs in the UK for common adult CT exams

Examination	DRL (mGy.cm)		Quantity
	Single slice CT (SSCT)	Multiple detector CT (MDCT)	
CT Head	760	930	KLP
CT Chest	430	580	KLP
CT Abdomen and pelvis	510	560	KLP

SHRIMPTON P C, HILLIER M C, LEWIS M A, DUNN M, 2005. Doses from computed tomography (CT) examinations in the UK- 2003 review, Report NRPB-W67. Chilton: NRPB-National Radiological Protection Board

Reference doses recommended for use as DRLs in the UK for common paediatric CT exams

Examination	Age	DRL (mGy.cm)	Quantity
CT Chest	0 – 1 y	200	KLP
	5 y	230	KLP
	10 y	370	KLP
CT Head	0 – 1 y	270	KLP
	5 y	470	KLP
	10 y	620	KLP

SHRIMPTON P C, HILLIER M C, LEWIS M A, DUNN M, 2005. Doses from computed tomography (CT) examinations in the UK- 2003 review, Report NRPB-W67. Chilton: NRPB-National Radiological Protection Board

Setting local diagnostic reference levels

- Radiology departments should set local DRLs with regard to appropriate international or national DRLs
- Local dose audit is used to check compliance with the local DRL
  - each time a dose audit is carried out the mean value is compared to the local and national DRLs
  - if the local DRL is exceeded an investigation should be triggered
- The national DRL may from time to time be derived from technology no longer in use in the radiology department
  - for example, the national DRL may have been derived from audit of screen-film radiography but the radiology department uses CR

22.5 DOSE MANAGEMENT

22.5.3 LOCAL DOSE AUDIT

Dose Management

- 22.5.1 Population-based dose surveys
- 22.5.2 Diagnostic reference levels
- 22.5.3 Local dose audit

Local dose audit

- The dosimetric techniques described previously form the basis of dose audit
- Patient data can be collected
  - every 3 to 5 years for each common X ray and CT examination,
  - and a few months after a new X ray installation
- In many situations a sample can be selected to best represent the population being studied and large enough to reduce the statistical error to an acceptable value

Local dose audit with small patient throughput

- If patient throughput is not sufficient to provide such a sample, constraints may be placed on the range of the appropriate anatomical parameter which is accepted for the survey
  - e.g. patient weight or breast thickness
- The dose for a typical patient may then be found
  - from the median of this distribution or
  - by interpolation of the sampled data to a standard patient size
- For paediatric patients it is necessary to use several size groupings

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