10 X Rays and X-Ray Regulations

> *"In the end, the public's health is at stake. An underexposed chest x-ray cannot reveal pneumonia, and an inaccurate radiation therapy treatment cannot stop the spread of cancer."*
>
> *Charles W. Pickering*

X-ray installations

The regulations on the handling of X rays are very similar to the regulations on standard radiation protection. The X-ray regulations in the European Union apply to those X-ray tubes and X-ray installations in which electrons are accelerated at least to 5 keV and in which they are limited to a maximum energy of 1 MeV. All installations in which electrons can be accelerated to energies beyond 1 MeV are subject to the regulations of standard radiation protection.

stray radiation

design approval

Devices and installations that produce unwanted radiation, like old-fashioned TV screens, where electrons are accelerated up to energies of something like 20 keV, do not require a license if a dose rate of 1 µSv/h at a distance of 10 cm from the surface is not exceeded or if they are approved by the competent authority by way of a design approval.

radiation exposures for patients

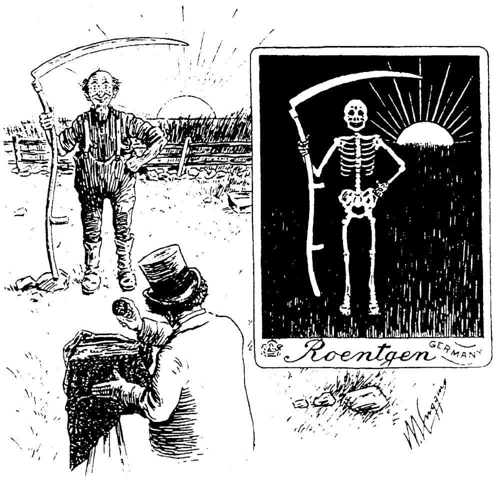
The X-ray regulations, of course, mainly concern X-ray tubes used for X-ray diagnosis and X-ray therapy on humans. It is desirable to obtain the best X-ray image available for a particular radiation exposure. At the same time one should try to reduce the radiation exposure by improving the X-ray detection system and image reconstruction without affecting the image quality. The radiation dose of the patient has to be documented. If the patient wants a copy of the documentation about the received X-ray doses, it has to be provided to the patient.

X-ray passport

Documents containing the information about the received X-ray doses have to be kept over a period of at least 30 years. Typical limits on the ambient-dose rate of X-ray tubes at a distance of 1 m from the focal point for a closed beam port would be 2.5 mSv/h for X-ray examinations and treatments using X-ray tubes with an accelerating voltage of up to 200 kV. The corresponding dose limit for X-ray tubes with voltages of more than 200 kV is 10 mSv/h.

In medical examinations with X rays those parts of the human body which are not examined must be shielded by a lead–rubber apron. A lead–rubber apron of 0.3 mm thickness reduces the intensity of 30-keV X rays already by a factor of 1000. For higher energies correspondingly lead–rubber aprons of higher thickness are

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_10,



“Smile!” Cartoon from the Journal ‘Life’ 1896

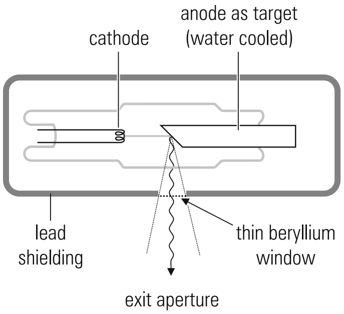


Figure 10.1
Sketch of an X-ray tube

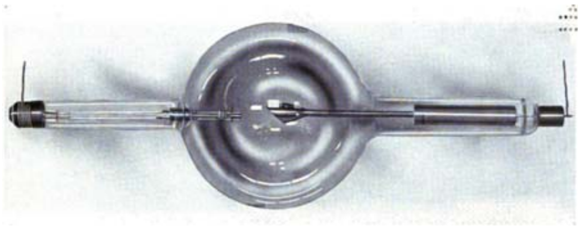


Figure 10.2
X-ray tube, from early 1900. The heated cathode is on the left, and the anode is on the right. The X rays are emitted downwards (The Coolidge X-ray tube: `http://commons.wikimedia.org/wiki/Image:Coolidge_xray_tube.jpg`; see also “The Cathode Ray Tube site”: `http://members.chello.nl/~h.dijkstra19/page5.html`)

required. For example, a lead shield of 1 mm thickness reduces the intensity of 50-keV X rays by a factor of 1000.

Figure 10.1 sketches the operation principle of an X-ray tube. Electrons from the cathode are accelerated onto a target (frequently tungsten) and produce bremsstrahlung X rays when they are decelerated in the anode. This continuous X-ray spectrum has discrete lines superimposed on it, which are characteristic for the target material.

X-ray bremsstrahlung

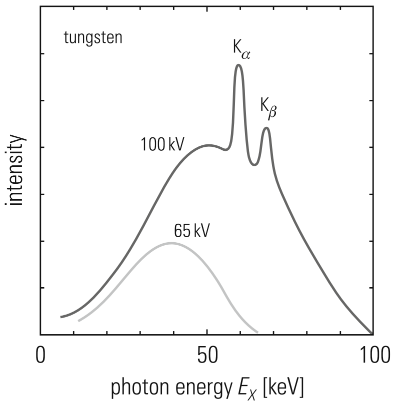


Figure 10.3
Energy spectra of an X-ray tube operated with voltages of 65 kV and 100 kV. The characteristic X rays of the tungsten anode are not excited for 65 kV

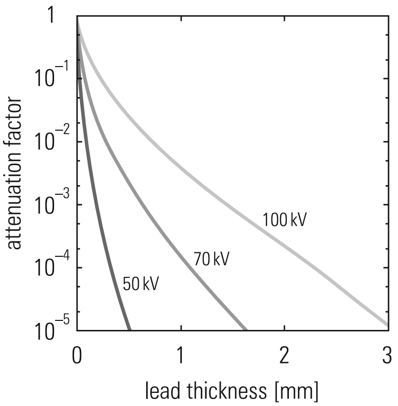


Figure 10.4
Attenuation factors of X rays in lead for three different operating voltages

characteristic X rays

Figure 10.3 shows the spectra of an X-ray tube with a tungsten anode for acceleration voltages of 65 kV and 100 kV. At the acceleration voltage of 65 kV the characteristic X-ray lines (K_α and K_β) of tungsten are not excited.[1]

shielding against X rays

Figure 10.4 shows the attenuation factors for X rays, produced by accelerating voltages of 50 kV, 70 kV, and 100 kV, and then filtered with 0.5 mm of aluminum. The attenuation curves are not perfect exponential functions because the X-ray spectra are continuous and the attenuation coefficients depend on the X-ray energy. In contrast to an attenuation factor of 1000 for monoenergetic X rays of 50 keV for a shielding of 1 mm of lead, the X rays generated by an

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[1] The characteristic X rays are called K, L, M, … lines. These lines are characterized by electron transitions from higher shells to lower ones. The K series provides short-wave X rays. K_α corresponds to a transition from the L to the K shell and K_β to a transition from the M to the K shell (see Fig. 3.12). Consequently, K_β X rays are more energetic than K_α rays.

X-ray tube operated with an accelerating voltage of 50 kV are attenuated by a factor of about 100 000 in a shielding of only 0.5 mm of lead. The reason for this is that the average energy of X rays for an accelerating voltage of 50 kV is only 30 keV and the absorption coefficient is a very steep function of the photon energy ($\sim 1/E_\gamma^{3.5}$).

documentation
storage of data
radiation areas
patient dosimetry

The radiation exposure of X-ray personnel has to be measured, documented, and stored for a period of 30 years. The definition of radiation areas follows that of the radiation-protection regulation exactly.[2] Just as in the field of radiation protection the radiation officer for X rays has to label the different areas correctly. Also it is the duty of the radiation officer to try to limit the exposure by X-ray examinations to a value as low as reasonably achievable. The radiation supervisor for X rays has to make sure that, for examinations on humans, a medical expert is consulted regarding the optimization of X-ray doses in the framework of patient dosimetry and quality control. The medical expert has to be a trained physicist or a scientist who is qualified also in the field of radiation protection.

qualified
X-ray-radiation personnel

It is highly desirable that the personnel operating the X-ray installations and also the medical doctors have the necessary qualifications and experience in the field of radiation protection with X rays.

10.1 Supplementary Information

Example 1

chest X-ray

A chest X-ray in the 1980s was usually performed at an anode voltage of $U = 80\,\text{kV}$. In medicine you will find it difficult to get the information from the doctor about the X-ray exposure in terms of µGy or µSv. They normally give information in terms of the product of the exposure time and the electron current in the X-ray tube. Typical values are around $I\,t = 2\,\text{mA s}$. Let us assume that the X-ray beam has a divergence of about 60° and the patient (area of the chest $A = 30 \times 30\,\text{cm}^2$) is at a distance of 1 m from the X-ray focus.

Figure 10.5
X-ray showing a frontal view of the hands (Source: RadiologyInfo™ `www.radiologyinfo.org/`)

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[2] As a reminder: limits on the effective doses in the European Union

surveyed area	$1\,\text{mSv/yr} < \dot{D} \le 6\,\text{mSv/yr}$
controlled area	$6\,\text{mSv/yr} < \dot{D} \le 20\,\text{mSv/yr}$
excluded area	$\dot{D} > 3\,\text{mSv/h}$
radiation-exposed persons category A	$6\,\text{mSv/yr} < \dot{D} \le 20\,\text{mSv/yr}$
radiation-exposed persons category B	$1\,\text{mSv/yr} < \dot{D} \le 6\,\text{mSv/yr}$
maximum occupational exposure over the whole life	$D \le 400\,\text{mSv}$

Figure 10.6
Siemens MAMMOMAT 1000 for analog mammography. This X-ray system is optimized for high-volume screening and regular mammographic views with high image quality at short exposure times

This information allows to estimate the X-ray exposure for a chest examination.

For an accelerating voltage of 80 kV the maximum photon energy is 80 keV and the average energy only 65 keV. A large fraction of the electron energy is lost as heat in the anode, so, the anode has to be cooled. Only a small fraction is emitted in the form X rays. This fraction can be described by

$$\eta_1 = 10^{-6} \times U\ Z\ ,$$

where U is the X-ray accelerating voltage in kV and Z the atomic number of the target. For $U = 80\,\mathrm{kV}$ and $Z = 74$ (tungsten) one obtains

$$\eta_1 = 6 \times 10^{-3}\ .$$

From the product $I\ t$ the number of electrons N_e hitting the anode can be worked out:

$$N_e = \frac{I\ t}{e} = \frac{2 \times 10^{-3}\,\mathrm{A\,s}}{1.602 \times 10^{-19}\,\mathrm{A\,s}} = 1.25 \times 10^{16}\ .$$

Figure 10.7
Normal posterior-to-anterior (PA) chest X-ray (source: RadiologyInfo$^{\mathrm{TM}}$ `www.radiologyinfo.org/`)

This yields a number of X-ray photons of

$$N_\gamma = \eta_1\ N_e = 7.4 \times 10^{13}\ .$$

Assuming that this fraction η_1 is completely emitted into the opening angle of 60°, and the distance to the patient is 1 m, and the illuminated area of the chest is $30 \times 30\,\mathrm{cm}^2$, the solid-angle fraction η_2 under which the X-ray tube 'sees' the patient can be worked out. One finds $\eta_2 = 8\%$. Therefore, the chest of the patient is hit by

$$N_\gamma^* = \eta_2\ N_\gamma = 5.9 \times 10^{12}$$

photons. Of these only

$$N_\gamma^*\ \left(1 - \mathrm{e}^{-\mu\,x}\right) = 2.7 \times 10^{12}$$

are absorbed in the patient, where $\mu = 0.03\,\mathrm{cm}^{-1}$ is the mass absorption coefficient and $x = 20\,\mathrm{cm}$ the assumed depth of the chest.

solid-angle fraction

absorption probability

For an average photon energy of 65 keV this corresponds to a deposited energy of

$$E = 1.74 \times 10^{17}\,\mathrm{eV} = 0.028\,\mathrm{J}\ .$$

partial-body dose

whole-body dose

This energy is deposited in a volume of $30 \times 30 \times 20\,\mathrm{cm}^3$ corresponding to a mass of 18 kg. This leads to a dose of 1.55 mGy. Converted to an effective whole-body dose (the tissue weighting factor for the chest is $w_i = 0.05$) leads to a dose of

$$H_{\text{eff}} = 0.078\,\text{mSv}$$

(the radiation weighting factor for X rays is 1, therefore, in this case, 1 Gy = 1 Sv).

In daily medical work it is, of course, impossible to perform these calculations for each individual case. Therefore, usually, the accelerating voltage, the product of exposure time and X-ray-tube current, and the tissue equivalent dose measured at the typical distance of the patient are given. Modern X-ray tubes use 120 kV and 5.6 mA s for a frontal chest examination. The patient usually is positioned at a distance of 150 cm from the focus and a field of view of $35 \times 43\,\text{cm}^2$ is defined. Under these conditions a dose–area product of $0.4\,\text{Sv}\,\text{cm}^2$, i.e. 0.27 mSv chest dose, corresponding to a 13.5 µSv whole-body dose for the patient is obtained. If the chest of the patient is X-rayed from the side, a typical voltage of 110 kV is selected, with a product of exposure time and current of 11 mA s for the same size of the image area at the same distance. A typical area-dose figure under this condition is $0.6\,\text{Sv}\,\text{cm}^2$ corresponding to a whole-body dose of 35 µSv.

direct chest X-ray

dose–area product

lateral chest X-ray

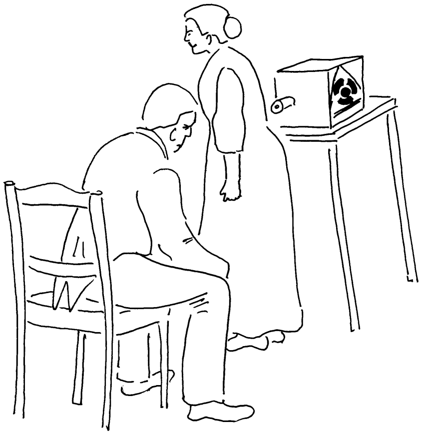
Example 2

electron microscope

microwave klystron

Installations and equipments which produce unwanted X rays are also subject to the X-ray regulations. Some of these installations even require a license. This is true e.g. for electron microscopes or microwave klystrons.

Even the old-fashioned TV sets using a vacuum tube for the TV screen generate soft X rays. In the European Union a limit is defined on the dose rate from such a device. This limit is given by the dose rate of 1 µSv/h to be measured at a distance of 10 cm from the



“I can’t see anything!”

© by Claus Grupen

TV sets

surface of the device. Exposures from a standard color TV set fall significantly below this limit. Also one has to consider that soft X rays are easily absorbed in air so that for typical distances from the TV set values of about 1 nSv per hour are obtained. This may lead to an annual dose in the µSv range for typical exposure times when watching TV. It is interesting to note that a low amount of radiation exposure watching TV can be traced back partially to the radioisotopes ^{40}K and uranium and its decay products, which are present in the glass of the TV tube. Modern TV sets with plasma or LCD screens (Liquid Crystal Display) do not create any X rays at all.

stray radiation

low-radiation displays

Unwanted X rays are also produced by old-fashioned monitors for computers. For long working hours at a short distance from the computer display, higher annual doses might be expected. However, most displays are well shielded against low-energy X rays and also against low-frequency electromagnetic radiation and, therefore, cause only a very small radiation exposure. This only applies to the old-fashioned displays using a vacuum tube for the display. The radiation exposure using flat screens is, of course, zero.

Example 3

microwave radiation

'electrosmog'

radar equipment

In the year 2001 high exposures of soldiers operating radar equipment were reported. Radar stations, of course, generate radar radiation which is a non-ionizing electromagnetic high-frequency radiation with frequencies in the gigahertz range. This microwave radiation can, of course – in a similar way as for microwave ovens or mobile phones – create a certain biological risk on humans ('electrosmog'[3]). This potential danger is not discussed here (see Chap. 15 on non-ionizing radiation), however, it has to be mentioned that the generation of radar rays is unavoidably accompanied by the creation of X rays. Radar equipment, therefore, produces X rays even though it is not its purpose to do so. In this case radar equipment is a typical generator of unwanted X rays.

klystron

magnetron

X rays in radar equipment are produced by the use of certain electronic components. Depending on the type of radar equipment klystrons or magnetrons are used to accelerate electrons with voltages of 20 to 100 kV. The deceleration of electrons creates X-ray bremsstrahlung in the energy range up to the maximum electron energy (i.e. up to a maximum of 20 keV or 100 keV, respectively).

In various newspapers conflicting information was given about the received doses. If the radar equipment is properly shielded, typical dose rates between 0.06 and 0.07 mSv/h are expected. However, occasionally the radar equipment was not shielded properly or was even unshielded. In such a situation maximum values of 10 mSv/h

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[3] a technical term constructed from the words 'electromagnetic', 'smoke', and 'fog' describing pollution by high-frequency non-ionizing electromagnetic radiation

have been measured which would correspond to an excluded area. Other estimations obtain exposures of up to 120 mSv per year: even in these cases, additional exposures by unshielded equipment during maintenance or calibration works were not considered.

An additional risk originates from the use of radium-containing material for displays of the radar equipment. During maintenance and repairs the radium-containing consoles were cleaned and partially machined. In this way highly toxic, α-emitting radium dust was very likely released into the breathing air. It is estimated that 20 000 people have operated such radar devices over a period of 25 years. Out of these 2000 cases of cancer have been reported, of which 200 were fatal, as reported by 'Medical Wordwide'[4]. Using the standard risk factor for lethal cancer incidence of 0.5% for the given age group and period, one would have expected about 100 fatal cases. It appears that the exposures during the running of radar equipment significantly increased the cancer-incidence rate.

radium dust

cancer incidence

Example 4

exposure due to X rays

An X-ray tube is operated in a laboratory at a voltage of 100 kV at 220 mA over a time of 600 seconds per week. A corridor passing at a distance of 5 m from the X-ray machine has to be shielded in such a way that it does not count as surveyed area. The X-ray machine is oriented towards this wall for 30% of the time. People passing through the corridor spend less than 25% of their time there.

workload mA min

The manufacturer of the X-ray tube has given an exposure of $K = 5\,\text{mSv}/(\text{mA min})$ at a distance of 1 m without shielding. A surveyed area is defined by a maximum dose limit of 1 mSv/yr for permanent residence.

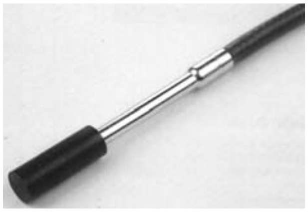

Figure 10.8
Diamond detector as solid-state ionization chamber for the relative dosimetry of X rays and beta rays; measurement range 80 keV–20 MeV for photons, 4–20 MeV for electrons (PTW–Freiburg, Germany)

The dose rate in front of the shielding wall at 5 m distance is

$$\begin{aligned}\dot{D} &= 5\,\frac{\text{mSv}}{\text{mA min}} \times 220\,\text{mA} \times 10\,\frac{\text{min}}{\text{week}} \times 52\,\frac{\text{weeks}}{\text{year}} \\ &\quad \times 0.3 \times 0.25 \times \frac{1}{25} \\ &= 1716\,\frac{\text{mSv}}{\text{yr}}\ .\end{aligned}$$

To reach the level of 1 mSv/yr the radiation has to be attenuated by a factor of 1716.

X-ray shielding

For an average X-ray energy of about 70 keV and a mass absorption coefficient μ of about $0.15/(\text{g/cm}^2)$ corresponding to 0.375/cm for concrete ($\rho_{\text{concrete}} = 2.5\,\text{g/cm}^2$) the required thickness is

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[4] I am grateful to Dipl. Phys. Helmut Kowalewsky for providing this information. Further details can be found at `www.m-ww.de/enzyklopaedie/strahlenmedizin/radarstrahlung.html`.

$$I = I_0\,\mathrm{e}^{-\mu x} = \frac{I_0}{1716}\ , \quad \mathrm{e}^{\mu x} = 1716\ ,$$

$$x = \frac{1}{\mu}\,\ln(1716) \approx 20\,\mathrm{cm}\ .$$

Summary

The X-ray regulations are independent of the regulation concerning the handling of radioactive sources. The X-ray regulations concern X-ray equipment and installations in which electrons are accelerated to a minimum energy of 5 keV and a maximum energy of 1 MeV. The limits given by the X-ray regulations are defined in a similar way to those of the radiation-protection regulations.

10.2 Problems

Problem 1

X-ray diffraction

X rays are used in the field of solid state physics for the determination of lattice constants (the spacing of atoms or ions in a regular crystal lattice). It is, however, only possible to resolve the lattice structures if they are larger than the wavelength of the electromagnetic radiation used. The question is, what kind of voltage has to be used for an X-ray tube, if structures on the order of magnitude of 0.5 Å need to be resolved?

To solve this problem one must consider that the maximum energy of photons ($h\nu$) is given by the accelerating voltage (eU). The frequency ν of the X-ray radiation is related to the wavelength λ via $\lambda\,\nu = c$ (h – Planck constant, c – velocity of light in vacuum).

Problem 2

The absorption coefficient for 50-keV X rays in aluminum is $\mu = 0.3\,(\mathrm{g/cm^2})^{-1}$. What is the required thickness of a wall made of aluminum to reduce the X rays by a factor of 10 000?

Problem 3

Let us assume that an X-ray tube operated with a voltage of 200 kV produces a dose rate of 0.7 mSv/h behind a concrete wall of thickness 20 cm. By an additional lead shielding on the outside of the concrete wall the dose rate should be reduced to a level of 1 µSv/h.

protective barrier against X rays

1. Work out the thickness of this additional lead shield.
2. What would have been the thickness of the shielding if one had wanted to reduce the dose rate to a level of 1 µSv/h by a lead shielding alone?

($\mu_{\mathrm{concrete}} = 0.3\,\mathrm{cm}^{-1}$ and $\mu_{\mathrm{lead}} = 11\,\mathrm{cm}^{-1}$ for an X-ray tube operated with an accelerating voltage of 200 kV.)