5. X-radiation
Diagnostic radiology and dosimetry

5.1 Medical reference and goal of the experiment

X-rays make up the high energy electro-magnetic X-radiation which is located right after the visible and ultra-violet light in the electro-magnetic spectrum . The radiation is reduced by absorption and scattering when passing matter. These effects depend strongly on the composition of the matter and are small in comparison to the absorption of visible light in opaque bodies. The matter therefore becomes practically transparent for the X-rays. The material dependent attenuation of the light results the formation of the contrast when radiographing bodies and can thus be used in medical diagnostics for inner structure imaging. On the other hand, the absorption of high energy radiation leads to the transmission of energy, which can damage the tissue through ionisation and eventual radical formation (radiation chemistry). While these processes can be used in radiation therapy to destroy tumour tissues, the damage to the healthy tissue has to be weighed against the advantages. To keep the radiation level for patients and employees to a minimum, while retaining maximum diagnostic and therapeutic benefits, a responsible physician needs knowledge in imaging, radiation effects and radiation protection, as well as the ability to determine the radiation dose quantitatively (dosimetry).
Through the experiment with a simple X-ray generator, you will get to know the principles of imaging, radiation protection and dosimetry.

Diagnostics: X-rays are used in medicinal diagnostics for the imaging of inner structures of the human body. Bones, teeth, the lung, and – by using a contrast medium – also the vascular system and the digestive tract. With the help of these images, pathological changes can be determined, operations can be planned, and the success of a treatment can be studied. In the usual X-radiation imaging, three-dimensional structures are projected onto a two-dimensional image plate. You will work in this experiment with a X-ray generator that possesses a well-shielded measurement area in which you can place different objects. X-ray images become visible either on a fluorescence screen or with the help of a storage plate. Additionally, you can determine the radiation intensity quantitatively with a measurement device. Through

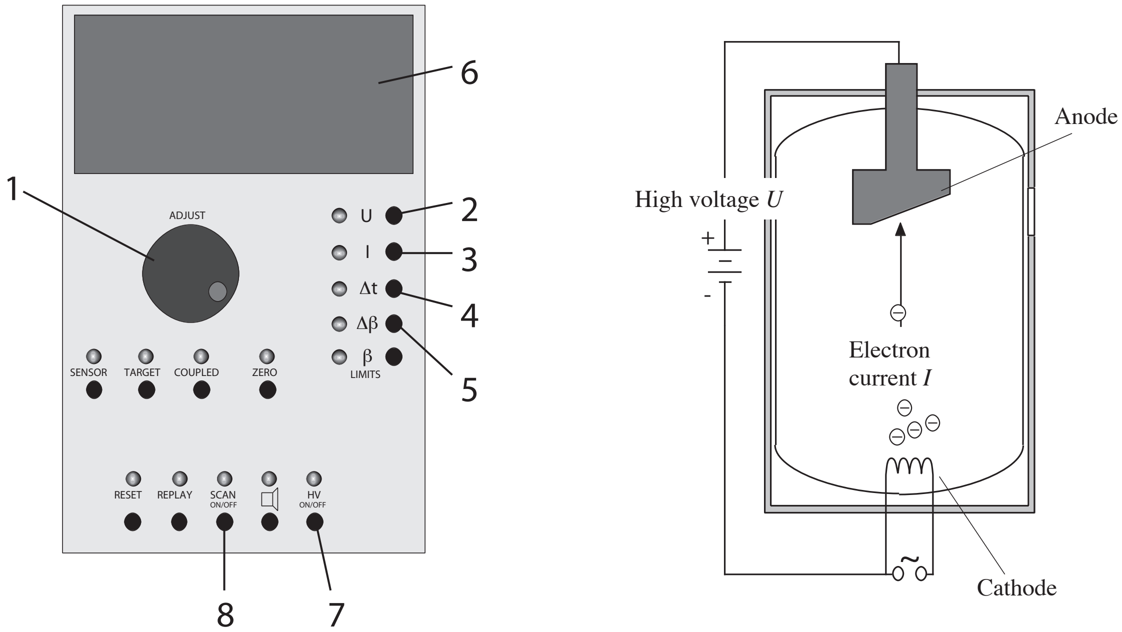

Figure 5.2.1: *Operation elements (left) and schematic of the X-ray generator (right). The enumerated elements are explained in the text.*

the experiment with this X-ray generator, you will get to know the principles of imaging. The geometric foundation (e.g. magnification and distortion) and the contrast formation by attenuation of radiation in the material.

Radiation protection and dosimetry: You will study radiation scattering, which is the main source for the radiation exposure level of employees, that carry out X-ray imaging. At the end, you will measure the ion dose in the air to quantitatively describe the ionising effects of the X-radiation. From this, the radiation effects on the biological tissues are calculated.

Safety Note: The generator used in this experiment is an inherently protected device that is also used in schools. As such, it possesses an adequate shielding towards the outside with lead and lead glass. With correct usage, X-rays can be produced by the generator only during closed shielding. *To ensure this safety measure, the rules and orders given by the instruction manual and the assistant are to be followed strictly during the experiment. Disregarding these or the improper operation of the generator will lead to the exclusion from the practical course.*

5.2 Experiment

5.2.1 Operating the X-ray generator

First, you will get to know the operation and the function of the X-ray generator. Fig. 5.2.1 shows on the left side of the sketch with the most important operation elements. On the right figure, the X-radiation generator is located behind a lead glass shielding (Fig. 5.2.1, right). It is an evacuated glass tube that is the source of the X-rays (only during enabled high voltage). On the right is the experimental area that is also shielded by lead glass.

- Turn on the device with the button on the left side wall of the device.

From the heated cathode, electrons are emitted. These are accelerated towards the anode, the beveled metal block above the cathode, to produce X-rays. This is done by a high voltage U, the so-called anode voltage, between the cathode and the anode (the anode is positive in relation to the cathode, cf. Part 5.3, *Physikalische Grundlagen*). This high voltage needs to be pre-chosen with the element U (2) and the wheel ADJUST (1):

- Press the element U (2). Then, the pre-chosen anode voltage (in kilovolt: kV) appears in the display window (6).

- Adjust the voltage using the wheel ADJUST (1) to 35 kV.

The anode voltage is now only pre-chosen and not yet turned on. Another parameter, that needs to be pre-chosen before turning on the high voltage, is the emission current I. That is the current that flows between the cathode and the anode when the high voltage is enabled:

- Press the element I (3). The pre-chosen emission current (in milliampere: mA) appears in the display (6).

- Adjust it using the wheel ADJUST (1) to 1 mA.

Before turning on the high voltage, you have to position an object to study into the experimental area and close it off. The practical course room should be shaded for the following experiment.

- Make sure that the so-called **collimator** is *NOT* not pinned onto the emission opening. It is a brazen cylinder with a slit that can be pinned onto the emission opening. This collimator is used later and not now.

- Hold down the button to the bottom left on the glass door to open the experimental area, while moving the door open.

- Place now the holder with the ballpoint pent onto an arbitrary place in front of the fluorescence screen (right) into the experimental area and close the glass door.

- Turn on the anode voltage and the emission current with the switch HV (7). That is only possible if both lead glass doors of the X-ray generator are closed firmly, due to radiation protection safety measurements. The light diode above the element blinks as long as the voltage is enabled. Through bremsstrahlung of the electrons on the anode, X-radiation is produced there. Part of the X-rays can access the experimental area from the left through an opening. Their arrival can be made visible with a fluorescence screen on the right side of the experimental area. In order to do that, take off the protection carefully (ask an assistant for help). Turn the high voltage off every single time before opening the glass door to the experimental area.

◇ What do you see on the screen (in comparison to the direct observation of the ballpoint pen)?

◇ How is the image produced – through lenses, mirrors, shadow, ...?

This procedure, observing the imagined object in real time on a screen, is called exposure in diagnostic radiology. It is used e.g. in angiography to study the movements of the interesting structures. Additionally, it serves as a constant control during surgery, e.g. when intra-cardiac catheters or cardiac pacemakers are involved. Turn off the anode voltage again, by using the element(7) again. *To protect the tube, do not enable/disable the anode voltage unnecessarily! Safety comes first, though. Turn it off every single time before opening the glass door to the experimental area.*

◇ Discuss: Can X-rays still be present in the experimental area when the anode high voltage is disabled and could they thus come out of the opened glass door?

5.2.2 Geometry of the imaging of an X-ray generator

You will study now how the form and contrast of the image depends on the settings of the exposed item and its position in relation to the X-ray source and the screen. The observed relationships are due to the same imaging techniques used in the medicinal X-ray diagnostics.

- Measure the lengths of the two metal strips on the Styrofoam cuboid and note it down into the following table.
- Place the holder with the cuboid such that one of the strips is located as close as possible to the fluorescence screen.
- Measure for both strips **cautiously** the distance to the screen (a suitable ruler is located in the work place) and write it into the table.

- ◇ Close off the experimental area and turn on the anode voltage. Measure the length of the image of the metal strips on the screen. Note down the measured values in the following table (units!).
- ◇ Calculate the magnification – the relation of the length of the image to the length of the object – each time.

	Metal strip 1	Metal strip 2
Length of the strip		
Length of the image		
Distance to the screen		
Magnification		

- ◇ Which strip seems bigger, the one closer to the screen or the one that is farther away?

- ◇ How does the magnification depend on the distance of the object to the screen? What does this mean for the imaging of a three-dimensional object such as e.g. the chest of the human body?

- ◇ Can you create scaled down images or images in the scale 1:1 with the X-ray generator? Where must the object be located approximately?

- Position the cube in the experimental area, such that one of the metal strips seems magnified to the **maximum**.

- Turn on the anode voltage and compare the images of the two strips.

◇ Which “side effects”does the large magnification have on the sharpness and the contrast of the image?

- Cover up the fluorescence screen again after the experiment.

5.2.3 Image contrast: Attenuation of the X-radiation

In a radiograph, not only the outer contour, but the**inner structure** of the body should be reproduced. These are only recognisable in the image by the **difference in brightness** that is created by the different attenuation of the X-rays. The attenuation of the X-radiation, that exists for the passage through matter, depends on the material, the layer thickness, and the radiation energy.

5.2.3.1 Material dependence of the attenuation

- Get a storage plate (photostimulable phosphor image plate) from the assistant to record the X-ray image.
- Place the test object into the holder (Fig. 5.2.2) and the plate behind the object, such that the light blue or white side of the plate looks towards the object. [1]
- Put the holder with the object and the plate in the corresponding hole of the experimental area. Close off the glass door.
- The X-ray image is to be recorded with an anode voltage of **17 kV** and an emission current of **1 mA**. Adjust the values with the elements U (2) and I (3), and the adjusting wheel (1).
- Adjust the element Δt (4) and the wheel (1) to an exposure time of **25 seconds**.
- The recording is started with the element **SCAN** (8) (NOT with the element HV!).

During the exposure, the object should not be moved. Try to avoid disturbances of the X-ray device during this time! After the exposure time is over, the anode voltage is turned off automatically. Give the plate to the assistant (to operate the readout computer, user knowledge is necessary). You will receive a print out of the X-ray image.

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[1] Some plates are less sensitive during first time use. If problems occurs, the assistant should delete the plate using the readout device.

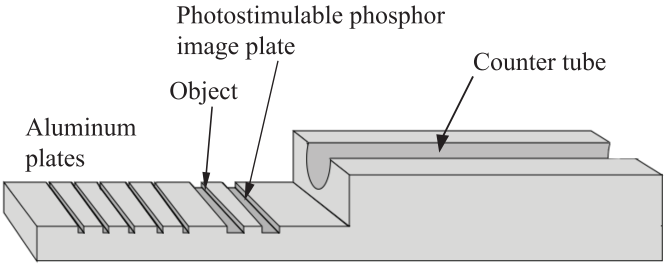

Figure 5.2.2: *Holder for the experiments to the attenuation law (counter tube and aluminum plates are used in the next part.)*

◇ What influence do the parameters U, I on Δt have on brightness or contrast?.

The X-ray machines are not completely identical. If one of the transitions between the materials is not detectable, change a parameter and repeat the recording. Glue your final recording into the notebook underneath Fig. 5.2.3. On the last recording, the material dependent attenuation is apparent.

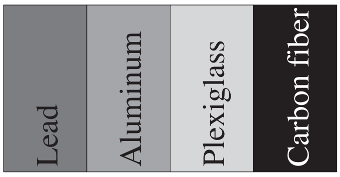

Figure 5.2.3: *Distribution of materials in the test object.*

X-ray image

- Use Fig. 5.2.3 as a guide to assign the different sections of the image to the various materials. Where is the image of the air gap? Consider that (especially important in diagnostic recordings) without any additional information or markings serious mistakes in the assignment could be made.

- Assign, in the following table, the different materials (including air) by their brightness of their recording. Note down the brightness qualitatively through (max. 10) crosses:

  high brightness ⇔ a lot of crosses   low brightness ⇔ few crosses.

- Note down the proton number into the third column of those elements that are contained in the material; you can find a periodic table in the last part of this book. Plexiglass and carbon fibers are based on organic compounds, whose main constitution is carbon in both cases. carbon fibers possesses with around 1600 kg/m^3 a slightly larger density than Plexiglass (around 1200 kg/m^3).

- In the fourth column, you should – also qualitatively coded with crosses – note down the attenuation of the X-rays by the corresponding material. You can assume that lead attenuates the radiation more strongly than air.

Attenuation of the X-radiation in different materials.			
Material	Brightness	Proton number	Attenuation

- ◇ If locations with high attenuation are depicted as dark, while low attenuation appears to be lighter, then this is a so-called **positive**, in the other case, it is a **negative**. How does the brightness depend on the attenuation in this X-ray recording/imaging on the fluorescence screen? Is a positive or a negative produced?

◇ How does the attenuation depend on the composition of the material, especially on the proton number of the individual components? The dependence on the proton number is shown most clearly for those materials that consist of only one element.

◇ How does the attenuation depend on the density, meaning the number of atoms per volume unit? Use for this the very faint, but recognisable contrast between Plexiglass and Carboniferous.

5.2.3.2 Layer thickness dependence of the attenuation

To study the dependence of the attenuation on the layer thickness, the intensity of the X-rays need to be **quantitatively** determined (and not only qualitatively through the brightness). For that, you have a counter tube available, that measures the **count rate** (in the unit 1/s) proportional to the intensity of the radiation.

- Plug the collimator (the metal cylinder with the small aperture) on the opening in the left wall of the experimental area until it latches. Then only a small bunch of X-rays can enter the experimental area.
- Take the holder out of the experimental area and screw in the plug on the cable of the counter tube in the socket, that is located on the back left side of the experimental area. The yellow plastic cap on the counter tube serves as a protection of the sensitive entry window; since the results of the experiment are not influenced by the plastic cap, it *should not be removed.*
- Put the holder back into the experimental area and put the counter tube, with the window facing the collimator, onto the holder.
- Adjust the emission current to **1 mA** and the anode voltage to **16 kV** and turn on the anode voltage to (**HV on**). The count rate N, measured by the counter tube, appears in the display window of the X-ray generator.

Caution: The display varies due to statical fluctuation of the intensity on the X-radiation generated by the anode. You have to observe it over several seconds and note down a corresponding average value. Think about how many reasonable digits you should note down for this value (and the calculated values from it) depending on this fluctuation.

- ◇ Now, measure the count rate N_0 (proportional to the intensity of the X-radiation!) and note them down in the second column. Use the emission currents I_E given in the following table.
- ◇ Slide one of the four aluminum plates (of the same thickness) into the slot in front of the counter tube and repeat the measurement for the three emission strengths and note down the count rates N_1 in the third column of the table.
- ◇ Repeat this with two, three, and four aluminum plates one after another. Note down the given relations of two count rates (intensities) into the 3 last rows.

Count rate as a function of the layer thickness.

I_E [mA]	N_0 [s^{-1}]	N_1 [s^{-1}]	N_2 [s^{-1}]	N_3 [s^{-1}]	N_4 [s^{-1}]
0.5					
0.75					
1.0					
I_E [mA]		N_1/N_0	N_2/N_1	N_3/N_2	N_4/N_3
0.5					
0.75					
1.0					

- ◇ How do the count rates (upper three rows) and their respective relations (lower three rows) depend on the emission current strength I_E? Can you give this relation also quantitatively (e.g. in form of a proportionality, quadratic or exponential relation)?

- ◇ Study the relations between count rates during a constant emission current strength: How can you describe the effect that you can achieve with another aluminum plate (of the same thickness!)?

- ◇ Which mathematical function describes the dependence of the intensities on the layer thickness?

5.2.4 Scattered radiation

The (different) attenuations of the radiation by tissue, bones, etc. are the requirements for the formation of contrast in X-ray images (radiographs) and thus for the diagnostic usage of X-radiation. At the same time, it has the undesirable effect that it can lead to tissue damage. The attenuation consists of two parts: **Absorption** and **scattering** (cf. Part 5.3, *Physikalische Grundlagen*). The ramifications of the scattering on the spatial intensity distribution of the X-rays will be studied in the following:

- **Take out the collimator again.**

- Remove the holder from the experimental area and put the counter tube into the small inclined holder in the **back** of the experimental area, facing to the **right**.

◇ Close off the experimental are and read (**anode voltage turned off!**) out the count rate.

Disabled anode voltage: $N =$

◇ Adjust the anode voltage to **30 kV** and the emission current to **0.7 mA**. **Turn on the anode voltage** and read out the count rate.

Enabled anode voltage: $N =$

◇ Put the plastic bottle, filled with water, in front of the screen in the experimental are (fill the bottle with normal water, if it is empty). Close off the experimental are and turn on the anode voltage (again at 30 kV and 0.7 mA) and read out the count rate.

Water filled plastic bottle in the path of the rays: $N =$

◇ Repeat the measurement with the **empty** plastic bottle in the path of rays, to investigate if the observed effect appears on the surface or in the volume of the bottle.

Empty plastic bottle in the path of the rays: $N =$

- Unscrew the plug of the counter tube from the socket and take out the counter tube and the holder from the experimental area.

◇ How can you explain the (different) influences of the different plastic bottles in the path of rays on the count rate? Why do the results for the **no** plastic bottle measurements during **enabled** or **disabled** anode voltage differ, even though the counter tube was not in the path of rays?

◇ What do you conclude for the danger to the body parts of the patient that are not part of the procedure and the employees that remain inside the room during the X-ray imaging? How does this danger for the employees, especially during **exposure**, depend on the “volume”of the patient?

5.2.5 Dosimetry

Absorption of X-radiation by the tissue mainly leads to the **ionisation** of the molecules in the tissue. This radiation is thus often also called **ionising radiation**. The ionising effect of the radiation is used in radiotherapy to damage tumour tissue. It must therefore be well-dosed. The basis for a quantitative specification of the radiation effect is the measurement of the ion dose (in a specific a material:):

The **ion dose** J is **the produced charge (of the same sign) per exposed mass**. The unit is therefore Coulomb per kilogram:

$$\text{Ion dose } J = \frac{Q}{m}\ ; \text{ unit } [J] = 1\frac{\mathrm{C}}{\mathrm{kg}},$$

where m is the exposed mass of the absorber and Q the absolute value of the charge of **one** sign created therein by ionisation.

◇ This part of the experiment consists of a determination of the ion dose that is created in the device for **a maximum anode voltage during one second in air**. This is has to be done for two different emission current strengths. To calculate the ion dose, you have to

1. calculate the mass m of the exposed air and
2. measure the produced charge Q therein.

1. **Calculation of the mass m in the exposed air**:

For the measurement of the ion dose (later!) a plate capacitor is to be installed into the experimental area. You can assume that between the capacitor plates coming from the entrance slit, a wedge-shaped air volume of $V = 125{,}4\ \mathrm{cm}^3$ is exposed.

◇ The mass of the exposed air is calculated from this volume and the density of air (for room temperature): $\rho_{\mathrm{air}} = 1{,}2\ \mathrm{kg/m}^3$ (units!).

$$m =$$

2. **Measurement of the produced charge Q in mass m:**

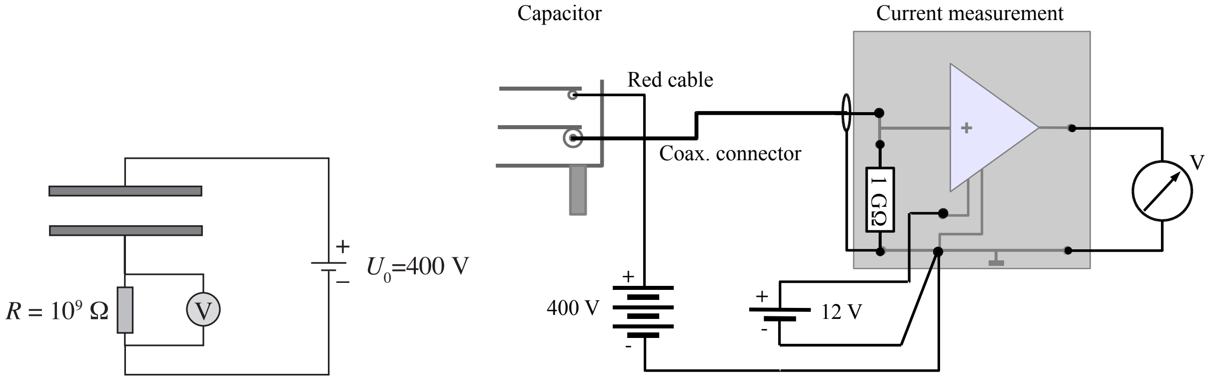

Figure 5.2.4: *Schematics (left) of the circuit (right) for the ion dose measurement.*

The charge measurement follows the following principle: A high voltage ($U_0 = 400$ V) is applied to the plate capacitor, which extracts the charge, produced by ionisation in the air between the plates. If in the time t the charge Q in the plate capacitor is produced and fully extracted, the current $I = Q/t$ flows through the circuit. Because the current I is too small for a direct measurement with an ampere meter, the voltage is measured with a voltmeter that is created on the resistance $R = 10^9\ \Omega$ by the current (cf. Fig. 5.2.4).

- Ask one of the assistants to mount the plate capacitor inside the experimental area together and build the sketched circuit in Fig. 5.2.4. Note: because of the – in comparison to the measurement resistor – *small* electric resistance of a voltmeter, almost the full current would bypass the measurement resistor itself and thus falsify the measurement. Therefore, a special component called impedance converter is placed between the measurement resistor and the voltmeter. It is pre-mounted (triangle symbol) on the pin board. Let the assistant check your finished circuit. *Then* you can turn on both voltages with their settings to maximum.

- Close off the experimental area and adjust the anode voltage to **35 kV** and the emission current strength to **1 mA** for the first measurement.

◇ Turn on the anode voltage and read out the voltage U on the voltmeter and note down the value in the second row of the table. Repeat the measurement for only half of the emission current (**0.5 mA**).

- Turn off the anode voltage and the X-ray generator.

◇ Calculate the current strength I from the voltage U and the resistance R in the plate capacitor from Ohm's law. Calculate from the current strength $I = Q/t$ how much charge is produced each time in the plate capacitor during the span of **20 seconds** and note down the values in the second and third row of the table (this time span depends on the used exposure time of your X-ray image. In medical reality, a much shorter exposure time is used.

	Symbol / unit	Emission current strength	
		$I_E = 1$ mA	$I_E = 0.5$ mA
Voltage	U /		
Current in the capacitor	I /		
per 20 seconds produced charge	Q /		
in 20 seconds produced ion dose	J /		

Calculation of the ion dose

◇ With the values for m and Q you can calculate the ion dose J from the definition $J = Q/m$ given before. Note down the values in the last table row.

◇ How does the ion dose depend on the emission current strength and the intensity of the X-radiaton? (The relation between the intensity and the emission current strength has been studied in the count rate measurement.)

Calculation of the energy dose

The measured ion dose does not yet reflect the damaging effect of the radiation on biological tissue. For this, the **equivalent dose** has to be calculated from the ion dose first, under consideration of the type of the tissue as well as the radiation. You will perform this calculation for the maximum emission current strength of 1 mA and will get to know the definitions of the further quantities that are relevant in dosimetry.

> The ion dose J is a relation for how much charge of a specific sign is produced per absorber mass.

This value depends on **which material** is exposed to the X-rays and for **how long**.

The energy dose D is a relation for how much energy per absorber mass is transmitted by the radiation onto the absorber.

Therefore:

$$\text{Energy dose } D = \frac{E}{m}\text{ ; unit } [D] = 1\frac{\text{J}}{\text{kg}} = 1\text{Gy (Gray)},$$

where m is the exposed mass of the absorber and E is the transmitted energy on the absorber. Since a direct measurement of the energy dose is often not possible, it is usually (just as in this experiment) calculated from the measured ion dose. For every ionisation, an average energy amount is transmitted to the target. If this energy amount is known, the energy dose can be calculated from the ion dose:

For air, the average energy transmittion is 33.85 Joule per Coulomb of produced charge (of one sign). This value comes from the average ionisation energy of air and the ionisation probability. The conversion from “ion dose in air” to “energy dose in air” is done via the multiplication with this factor:

$$D_{\text{air}} = J_{\text{air}} \cdot 33.85 \text{ Gy/(C kg}^{-1}\text{)}.$$

To calculate the energy dose in another material, it is necessary to know the **dose conversion factor** f (dimensionless) for the corresponding material:

$$D_{\text{X}} = f_{\text{X}} \cdot D_{\text{air}}$$

where the index “X”stands for the corresponding material.

◇ For muscle tissue, the dose conversion factor is e.g. $f_{\text{muscle}} \approx 1.1$ (for other types of tissue, e.g. bones or fat, it depends additionally on the energy of the radiation). Calculate the energy dose that muscle tissue would absorb in the described conditions in the X-ray generator during 20 seconds:

$D_{\text{air}} =$

$D_{\text{muscle}} =$

Calculation of the equivalent dose

From the energy dose, the **equivalent dose** is gained by the multiplication with a **figure of merit** q. The figure of merit incorporates the different biological effects of the various types of rays. For X-rays, it is defined as 1 (the biological effects of other types of ionising radiation is taken in relation to X-rays; you can find a table in Part 5.3, *Physikalische Grundlagen*). The unit of the equivalent dose is Sievert (Sv).[2]

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[2] This is only another name for the same physical unit J/kg. The change in name is there to simplify the discrimination of the adjusted and unadjusted quantity.

The equivalent dose H is a relation for the biological effect of the radiation.

$$\text{Equivalent dose } H = q \cdot D \text{ ; unit } [H] = 1\frac{\text{J}}{\text{kg}} = 1\text{Sv (Sievert).}$$

q is the figure of merit of the radiation, D the absorbed energy dose.

◇ Calculate the equivalent dose that muscle tissue would absorb in the described conditions in the X-ray generator during 20 seconds:

$H_{\text{muscle}} =$

Calculation and comparison of the equivalent rate

To all the defined dose quantities, another one can be added, the **dose rate**: the corresponding dose depending on the time (usually made apparent by a small dot above the formula letter of the corresponding dose quantitiy). So e.g. the **equivalent dose rate $\dot{H}$** is defined as

$$\text{Equivalent dose rate } \dot{H} = \frac{H}{t} \text{ ; unit } [\dot{H}] = 1\frac{\text{Sv}}{\text{s}}.$$

Where t is the time, during which the equivalent dose is recorded.

◇ What equivalent dose rate would the muscle tissue absorb under the given conditions in the X-ray generator?

$\dot{H}_{\text{muscle}} =$

This equivalent dose rate is very high in comparison with the normal radiation exposure of about 2.4 mSv/a (1 a = 1 year). The equivalent dose rate inside the experimental area is high, mainly due to the low anode voltage used. This produces a lot of low energy X-rays. But this low energy radiation is attenuated towards the outside very efficiently by the lead(glass)-shielding, such that the equivalent dose rate in a distance of 10 cm next to the generator amounts to less than 0.001 mSv/h (1 h = 1 hour).

◇ Compare the equivalent**dose** (H_{normal}), that you absorb during an afternoon course (3 h) through **normal** radiation exposure and the equivalent**dose** ($H_{\text{X-ray generator}}$), that you absorb in the same time through the operation of the X-ray generator in addition (with the assumption that the generator is running half the time (1.5 h) at maximum power).

$H_{\text{normal}} \approx$

$H_{\text{X-ray generator}} \approx$

5.3 Physics behind this experiment

This section only exists in the German version of the lab manuals.