Chapter 3

Radiation Principles and Safety

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Additional information is available at the end of the chapter

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1. Introduction

Interventional cardiology today without the use of x-ray technology cannot even be imagined. This is also true for medicine in general. The radiology era begins with the discovery of the x-rays by Wilhelm Conrad Röntgen, on the November 8th 1895 (following the transliteration conventions for the characters accentuated by 'umlaut', „Röntgen“ is in English spelled „Roentgen“, and with that spelling is most often found in the literature). On that day he produced and detected for the first time the electromagnetic radiation in the wavelengths today known as the x-rays, for which he received the Nobel prize for physics in 1901 [1]. This was the start of radiology, which has developed tremendously over the years. In time, radiology adopted other forms of human body imaging (magnetic resonance, positron emission tomography etc.), but even today the most radiologic studies in the world are performed using the x-rays, whether in the form of classic x-ray imaging, computer tomography, or various forms of fluoroscopy and/or fluorography, which is used in interventional cardiology. The term 'fluoroscopy' depicts viewing of structures in real time, while 'fluorography' means that different methods of image aquisition and storage for later review are being used.

X-ray radiation is a form of electromagnetic radiation. X-rays are electromagnetic waves with a wavelength in the range of 0.01 to 10 nanometers, which corresponds to frequencies in the range 30 petahertz to 30 exahertz (3×10^{16} Hz to 3×10^{19} Hz) and energies in the range 120 eV to 120 keV. X-rays are shorter in wavelength than ultra-violet rays and longer than gamma rays. In many languages, X-radiation is called Röntgen radiation, after Wilhelm Conrad Röntgen, who is usually credited as its discoverer, and who had actually named it X-radiation to signify the up to then unknown type of radiation [1].

X-ray input doses for fluorography are generally 10-fold higher than those used for fluoroscopy. This is why fluorography is the major source of the radiation dose [2]. Procedures which include the use of x-rays are associated with the exposure of the patients to a certain amount of x-ray radiation, and in some cases, especially in interventional cardiology, the staff is also exposed to this form of radiation. The constant evolution of interventional cardiology, with ever more complex procedures demanding prolonged fluoroscopy and fluorography time, as well as the demands for better imaging of small structures (guidewires, angioplasty balloon- and stent-markers, stents themselves, intravascular ultrasound probes, etc.) associated with higher exposures to larger amounts of x-ray radiation, have all raised the question of radiation protection, both for the patients and the staff inside the catheterization laboratory (cath lab). Occupational doses of radiation in interventional cardiology procedures guided by fluoroscopy are the highest doses registered among medical staff using x-rays. The use of ionizing radiation increases the risk of malignant disease occurrence and can cause skin or eye damage to both the patient and the personnel [3].

2. How the x-ray radiation is produced

2.1. The x-ray tube

The principle of generating the x-rays is basically the same in all x-ray machines. The source of x-rays is the x-ray tube (fig.1, fig. 2). Within it are the cathode and the anode (fig. 1). The electrically positive tungsten anode is bombarded with accelerated electrons originating from the electrically negative cathode. When the high-velocity electrons collide with the anode, they lose most of their energy (~99%) as heat, and a small fraction (~1%) as x-rays. Since the electrons are slowed down within the anode by different segments of atoms and mostly multiple interactions with several atoms within the material itself, they release a variety of x-ray energies. However, when all of the electron's energy is lost in a single interaction, the resultant emitted x-ray has the highest possible energy, equivalent to the voltage applied across the tube. That is reffered to as the kVp, or 'peak kilovoltage' of the emitted x-rays. A typical x-ray tube ranges from 60 kV to 120 kV. The tube current, measured in milliamperes (mA) is defined as the number of electrons that arc from the cathode to the anode per second [4]. Modern x-ray tubes generate the radiation in pulses rather than in a continuous form, and those pulses are synchronized with the other components in the fluoroscopic/fluorographic system. The duration of the time during which the electrons hit the anode is the pulse width, and is measured in milliseconds (ms).

The anode is made of tungsten because this material can withstand very high temperatures without melting. As stated before, some 99% of the energy which the electron beam is losing when hitting the anode is heat. The anode is constructed as a disc, and to reduce the heat strain even more, it is constantly rotated at speeds up to 10,000 rpm (fig. 1). This way, the area bombarded by the small electron beam is not actually a single spot, but a circle track. The small area of the anode which is being bombarded by the electron beam, and from which the x-rays are emitted is called the 'focal spot', and since the anode is being rotated, the focal spot is actually the already described circular track on the anode disc. The size of the focal spot affects the image quality in different ways. If it is smaller, the images are sharper, but if it is larger, it can produce more x-rays. The cathode is a tungsten wire, and is the source of electrons which are accelerated towards the anode. The cathode is heated to high temperatures by passing the current through it, and is maintained at a large negative voltage relative to the anode. The electrons are 'fired away' from it and accelerate toward the anode, hitting it as they reach their maximum energy, which is 60 kV to 120 kV.

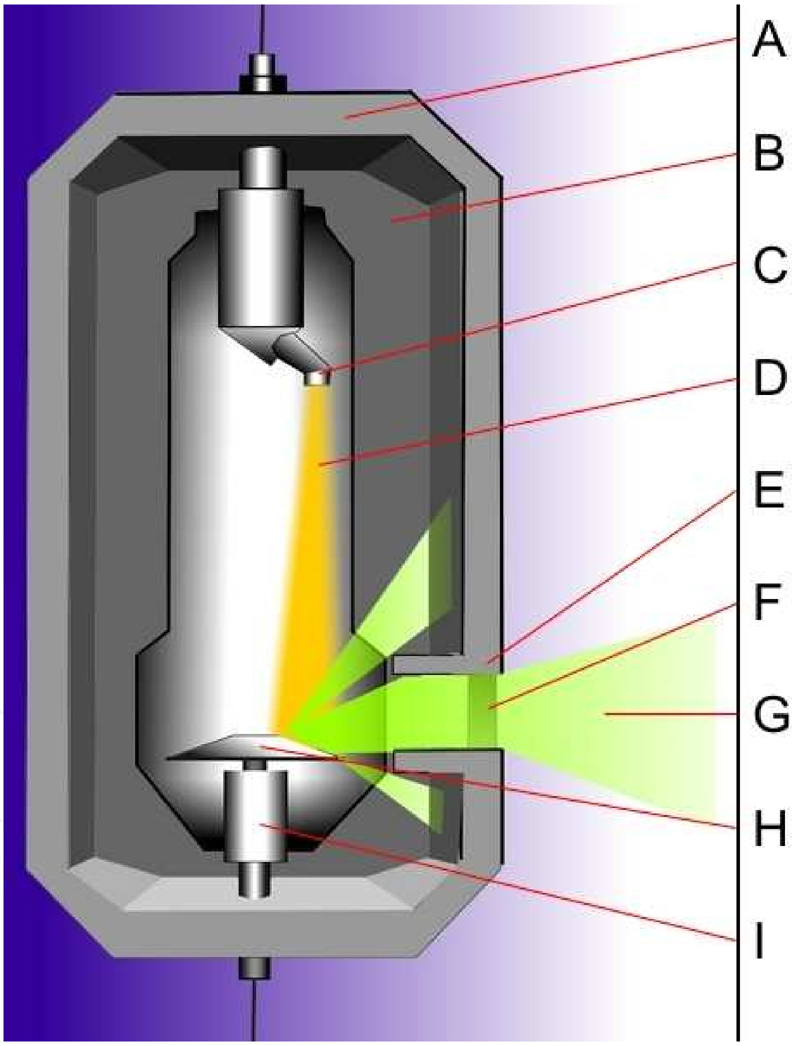

Figure 1. The x-ray tube. Legend: A – housing; B – oil bath for cooling; C – cathode; D – electron beam; E – collimators; F – filters; G – x-rays; H – anode; I – engine for anode rotation (illustration: J. Čaluk).

Figure 2. X-ray tube

2.2. Filters

As the electrons are slowed down by the anode, there occurs a spectrum of different wavelength x-rays called the brake-radiation (in German: Bremsstrahlung), with spikes of x-ray energies at characteristic wavelengths when all the energy of an electron is lost at a single collision, as noted earlier. The brake-radiation is mostly of low photon energies (<25-30 keV), and would be mostly absorbed in the patient's superfitial tissues. Therefore, the brake-radiation would not contribute to generating the x-ray image, but would, on the other hand, increase the amount of radiation to which the patient is exposed. This is why these x-rays are filtered in the beam exit port, and the filters applied selectively absorb the x-ray photons from this region of the energy spectrum [4]. Modern systems usually use copper filters 0.2 – 0.9 mm thick. Since these filters attenuate the x-ray beam (fig. 1), this requires an increased tube output, and when this is accomplished, the greater energy output occurs in the energy range of interest. Filters are basically simple, small metal sheets. In addition to the permanent beam filtration that is usually equivalent to 3 mm of aluminium, all cardio-angiographic equipment should have heavily filtered x-ray sources. The number and the mode of filter use differs among manufacturers, but optional filters of 0.1 mm, 0.2 mm, 0.3 mm, etc. should be available to order with the machine. In some products, users can employ different dose-management modes, and these filters might be incorporated into those modes, selectable by the user.

The thickest filters would therefore be used for smaller patients, and the thinnest ones for large patients. Since the filters primarily eliminate the useless part of the x-ray beam, but also do attenuate even a part of the useful beam, the goal of filtration is to produce the best possible compromise between image quality and radiation dose.

2.3. Collimators

In order to adjust the shape and the size of the x-ray field emerging from the tube, lead collimators which completely absorb the x-ray beam are used. They actually limit the exposure of the patient only within the region of interest, and thus reduce the unneccessary exposure to both the patient and the staff. The collimators can be manipulated as to further reduce the port of the x-ray tube (fig. 1) and by that, to reduce the irradiated area. The edges of the collimator blades are then visible in the imaging field as shadows. The amount of absorbed and scattered radiation can be reduced by an adequate collimation –the entrance surface area of the x-ray beam on the patient's skin should be reduced to the smallest possible/needed size [5,6,7].

2.4. X-ray generators

The x-ray generator provides the electric power to heat the cathode, to accelerate the electrons from the cathode to the anode thus generating the x-ray beam, and to turn the x-ray pulses on and off. It automatically adjusts the tube voltage, current, and pulse width to maintain a certain image quality. In interventional cardiology, there is a demand for generators able to provide up to 100 kW of power across all the voltages in the diagnostic range. The modulation of variables of x-ray beams is automated, and it maintains constant brightness at the image receptor as the thickness of patient's tissues varies with different projections and angulations. Very oblique angulations mean that the tissue thickness is bigger, and more powerful radiation is required to generate the image in comparison to less or non-angulated tube positions. Also, the image quality must be maintained regardless of the patient's built, so bigger patients are exposed to higher amounts of radiation, because stronger x-ray beams are required to penetrate their bodies [8,9]. Image brightness at the oputput of the imaging chain is rapidly sampled. The measurements are sent back to the generator to modulate the above mentioned variables and provide the desired image brightness. Beside the pulse width, the voltage, and the current, the parameters which can be altered are camera aperture and electronic amplification gain.

3. X-ray image formation

The x-ray beam directed towards the patient is considered to be uniform. After interacting with different tissues which attenuate it to a variable degree, a non-uniform x-ray beam exits the patient. Its non-uniformity, generated by the process of x-ray absorption in the patient, is the basis for obtaining an x-ray image. The degree of 'darkness' in the x-ray image, which forms the x-ray 'shadow', is determined by the energy of the original x-ray beam generated by the tube, the thickness of the exposed object (patient's tissues), and the elemental makeup of the object (patient's tissues). The removal of the x-ray beam as a function of the object thickness is exponential, but the elemental makeup of the tissue is characteristic for the tissue itself, and as a function is characterized by a linear attenuation coefficient. Half-value layer (HVL) is the parameter defined as the thickness of a tissue sample that absorbes (removes from the beam) one-half of the beam intensity. Regarding the beam energies used in interventional cardiology, HVL for muscle would be 3.2 cm, for bone is 1.5 cm, for iodine is 0.01 cm (100%), and as a comparison, for the lead, the HVL is 0.01 cm [4].

Figure 3. Image intensifier

When a non-uniform x-ray beam leaves the patient's body, its spatial distribution is the basis for forming an x-ray image. It contains the information on the anatomy of the scanned region, and if it is taken within a defined time-frame, it can also be used for the assessment of the patient's physiology. But, since the spectrum of x-rays cannot be detected by the human eyes, it must be 'translated' into visible information. There are several technologies currently in use for that purpose, and the most common being used in interventional cardiology today are image intensifier and digital flat-panel detector technology, both of which are digital. Although our senses use the analogue method to percieve the reality, for the purpose of securely storing the information and being possible to make exact copies, and later review the information without quality loss, that information needs to be digitalized. The digital-flat panel detectors are the state of the art now, but still the vast majority of the systems currently in use employ the image intensifier technology (fig. 3). The main role of

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the image intensifier is to convert the x-ray intensity information into the visible light spectrum and expose photographic film or a video camera. The details of the process taking place within the image intensifier are beyond the scope of this chapter and are discussed elsewhere.

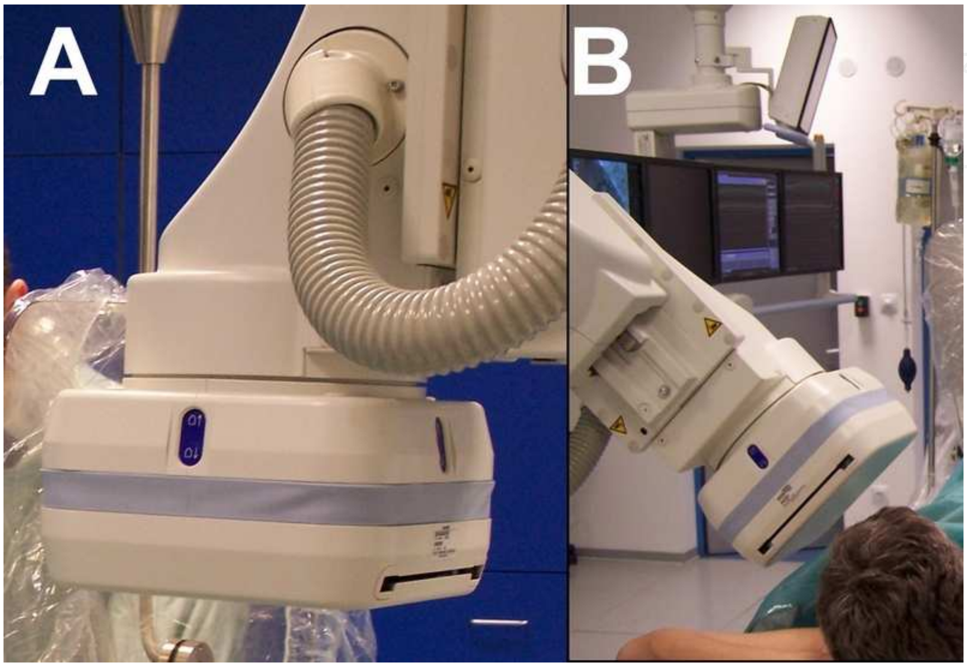

Figure 4. Digital flat-panel detector

However, recently a novel technology has been introduced and its use in cardio-angiography is constantly increasing: the digital flat-panel detector (fig. 4), which consists of (simply speaking) several layers of material. The x-ray photons, upon leaving the patient, hit the input phosphor layer of the detector, and it produces light photons. Behind that layer is the photodiode and the thin-film transistor layer. The generated light photons produce electric signals within this layer, and those signals are captured as voltages in the discrete flat-panel elements [4]. A typical panel consists of 1024 x 1024 elements over a rectangle-shaped field of view. Each flat-panel element's voltage signal is converted from an analogue voltage to a digital representation. The digital image produced like this is represented using a fixed number of values, and those are distributed over a limited set of co-ordinates. This information can then be stored or copied. For viewing, it is fed through conversion system and into the viewing monitor, and we percieve it as an image, with monitor pixels corresponding to flat panel detector's elements which received the beam. In order to standardize the digital communication within the medical community, the DICOM (Digital Imaging Communications in Medicine) system has been introduced. It is used for organizing the image data in such a way that other users of the DICOM system can review those data accurately, and is currently the standard-one in medicine.

4. Radiation management and safety

X-ray radiation is a carcinogen [10]. No dose of radiation may be considered safe or harmless [11]. It can also cause severe injury called radiation burns, but the likelihood of that is extremely low when the fluoroscopy/fluorography is adequately managed. Doctors, nurses, technicians, and other medical staff working in radiation environment, who have accumulated significant doses of radiation through their careers have been shown to develop some form of radiation-induced health-problems, the most important being cancer, cataracts, and skin injury [12,13]. Interventional cardiologists, working at very low distances from x-ray tubes, and the patients who are also the sources of scattered radiation, are at particular health risk.

4.1. Radiation effects

Effects of radiation can be generally divided into two basic groups: the stochastic effects, and the deterministic effects. Both groups are very important for the pathological consequences on the human body.

Stochastic effect occurs within a single cell and makes it adversely functional. This happens because of an alteration of an important macromolecule (such as the DNA) and can result upon a single interaction with radiation. It is therefore logical to assume that this kind of effects may occur with any radiation dose, but in practice, low doses of radiation carry an extremely low risk of stochastic effects on the body. The most important stochastic effects in the clinical sense are the occurrence of radiation-induced tumors and heritable changes in reproductive cells. The risk of these effects occurring rises with the rise of the amount of radiation to which a person is exposed, so the induced cancer becomes measurable in exposed adults at doses over some 100 mSv. In children, and in fetus (if a pregnant woman is exposed to radiation), even lower doses have been defined as carcinogenic. The stochastic risk of inducing malignant disease associated with radiation is small but definite [14].

Deterministic effects are the result of damage to a large number of cells, therefore a certain dose of radiation has to be applied for these effects to take place. This minimal dose for a deterministic effect is called the threshold dose. The higher the dose (above the threshold), the more severe the effects. Some examples of deterministic effects are: skin erythema, epilation, dry or moist desquamation, secondary ulceration, ischemic dermal necrosis, various stages of dermal atrophy, induration, teleangiectasia, late dermal necrosis, vision-impairing cataract [10]. Some authors propose that skin cancer can also be considered to be a deterministic effect of radiation.

For both of these groups of radiation effects there exists a time delay between the exposure to radiation and the clinical manifestation of the effect itself. This delay ranges from days to weeks to months for deterministic effects, and for malignant diseases, from as little as 2 years, to as long as many decades. In many cases, neither the patient, nor the physician (usually a dermatologists or a general practitioner) grasps the connection of a skin disorder (usu-

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ally an erythema, or a 'radiation burn') and a previous interventional cardiology procedure, because of this time delay – usually several weeks.

4.2. Units of measurement of x-ray radiation

In order to understand and quantify the effects of radiation on humans, different units of measurement have been developed. It is necessary to know these units as to be able to apply the safety measures in radiation environment, as well as to compare the health-risks of different forms of radiation.

Absorbed dose is the amount of radiation energy absorbed by a particular tissue. The x-ray radiation interacts with living tissues upon entering them, and its energy causes molecular changes, and therefore has the potential to have biologic effects. The unit of absorbed dose is gray (Gy), meaning that 1 Gy is the radiation energy of one joule (1 J) concentrated in one kilogram (1 kg) of tissue.

Equivalent dose is an estimate of the biologic potency which a form of radiation might have for an absorbed dose, and is determined by the properties of the radiation itself. Therefore, for different kinds of radiation, the equivalent doses can be different, although the absorbed doses can be the same. This is actually a safety term that can be used to compare the biologic potency of different kinds of radiation. The unit for equivalent dose is sievert (Sv). In interventional cardiology, 1 Sv is considered to be equivalent to 1 Gy [10].

Effective dose is the estimate of a hypothetic dose which would have to be delivered to an interventionist's entire body to have the same risk for the radiation adverse effects as the non-uniform doses which are actually delivered. The need for establishing this unit of measurement occurred because during the procedures in the cath lab (or similar radiation environments), some of the body parts are better protected (e.g. internal organs), while other body parts are less, or not at all protected (e.g. head and limbs), under the assumption that they are less radiosensitive. Therefore, the spatial distribution of radiation exposure is non-uniform. Effective dose eliminates this complexity in radiation risk assessment. The unit to measure the effective dose is sievert (Sv), and in interventional cardiology 1 Sv can be considered to be equal to 1 Gy of x-ray radiation absorbed uniformly in the body.

There are, of course, the proposed limits to which personnel in the radiation environment can be exposed. Regarding the effective dose, the limit for the staff is 100 mSv in a consecutive five year period, subject to a maximum effective dose of 50 mSv in any single year. The equivalent dose for the lenses of the eye should be limited to 150 mSv in a year. The limit on equivalent dose for the skin should be 500 mSv in a year, and the dose for the hands, forearms, feet, and ankles should be limited to 500 mSv in a year [11].

4.3. Limiting the exposure to radiation

The basic rule which can be applied regarding radiation protection is: 'what is good for the patient is also good for the staff'. For this reason, radiation protection measures will be discussed in general, with additional comments regarding the staff or the patient when necessary. The four basic methods of limiting exposure to radiation can be remembered by using the mnemonic TIDS, which stands for: time, intensity, distance, and shielding [10].

The time of fluoroscopy/fluorography should be limited to the necessary minimum. A good measure for orientation regarding this is fluoroscopy time recorded by most machines used for cardio-angiography today. Although, most devices show only fluoroscopy time, and the operator must also think about the fluorography time, knowing that the amount of radiation for the same amount of time is in fluorography 10-fold of that in fluoroscopy. Some devices have the ability to show fluorography time, or a complete beam-on time. In addition, a trend towards less fluoroscopy time is obvious with more experienced operators. However, more experienced operators are more often involved in complex procedures, which actually prolong the fluoroscopy time. Regardless of that, all operators have to be aware that they must reduce the beam-on time to a minimum provided that they can visualize the structures of interest and complete the procedure safely. Complex procedures, such as multivessel interventions, treating chronic total occlusions, or bifurcation lesions demand more procedure time than the simple interventions, and this leads to increased radiation dose when treating more complex coronary disease [16]. Some practical advices: when documenting balloon inflation, just a short single shot should be enough, there is no need to prolong the shot of an inflated balloon; there is no reason to record or observe the gradual balloon deflation, this can be checked with short beam-on shots; the operator’s foot should be kept away from the fluoropedal when not actually using fluorography, as to not accidentally step on the pedal and produce unnecessary radiation; a diagnostic fluorography can in most cases (but not always) be limited to a single cardiac cyclus; direct stenting can also be used and is proven to reduce beam-on time [17,18].

Intensity of radiation should also be minimized. This can be done in several ways. As noted earlier, the tube current and voltage can be modulated up to a point. An easier way to reduce the intensity would be by reducing the pulse rate, in some devices marked as ‘frame rate’. This can also be done to a point where the radiation is minimal, while the images are adequate for performing the procedure.

Distance from the source of radiation must be maximized. It is advisable for the operator to stand away from the tube as much as possible, while being able to operate the equipment, the catheters, syringes, etc. Regarding the other staff in the cath lab, anyone who is not needed inside the room should leave the room, but be readily available to enter as soon as they are needed. All the members of the staff who must stay inside the cath lab should keep their distance from the radiation source at all times, but be ready to attend the patient, or assist the operator on demand. Even small increase of distance from the source of radiation is important, because for each doubling of distance from the source, the intensity of radiation is reduced 4-fold.

Shielding of personnel from the radiation is also of utmost importance. The radiation shields come in several types. The ones above the patient are connected to an anchor point in the ceiling and should be moveable, so that they can be adjusted to the pa-

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tient's position and size (fig. 5, fig. 6). These shields protect the operator and the assisting staff from the radiation scattered from the patient's body. Some cardio-angiographic tables have the lower shields attached at the table sides, and the angulation of those shields can be altered to provide the best possible operator and staff protection from the scattered radiation off the posterior aspect of the supine patient, but also from the radiation generated by the tube, which is located beneath the patient (fig. 5, fig. 6). These shielding drapes significantly protect the operator from scattered radiation [19,20]. In some cases these shields are not connected to the tables themselves, but are free-standing. These shields protect the operator's legs and feet, which are among the most exposed body parts of the operator. There is further shielding in the walls, floors, and the ceiling of the cath lab in order to protect the people outside the cath lab.

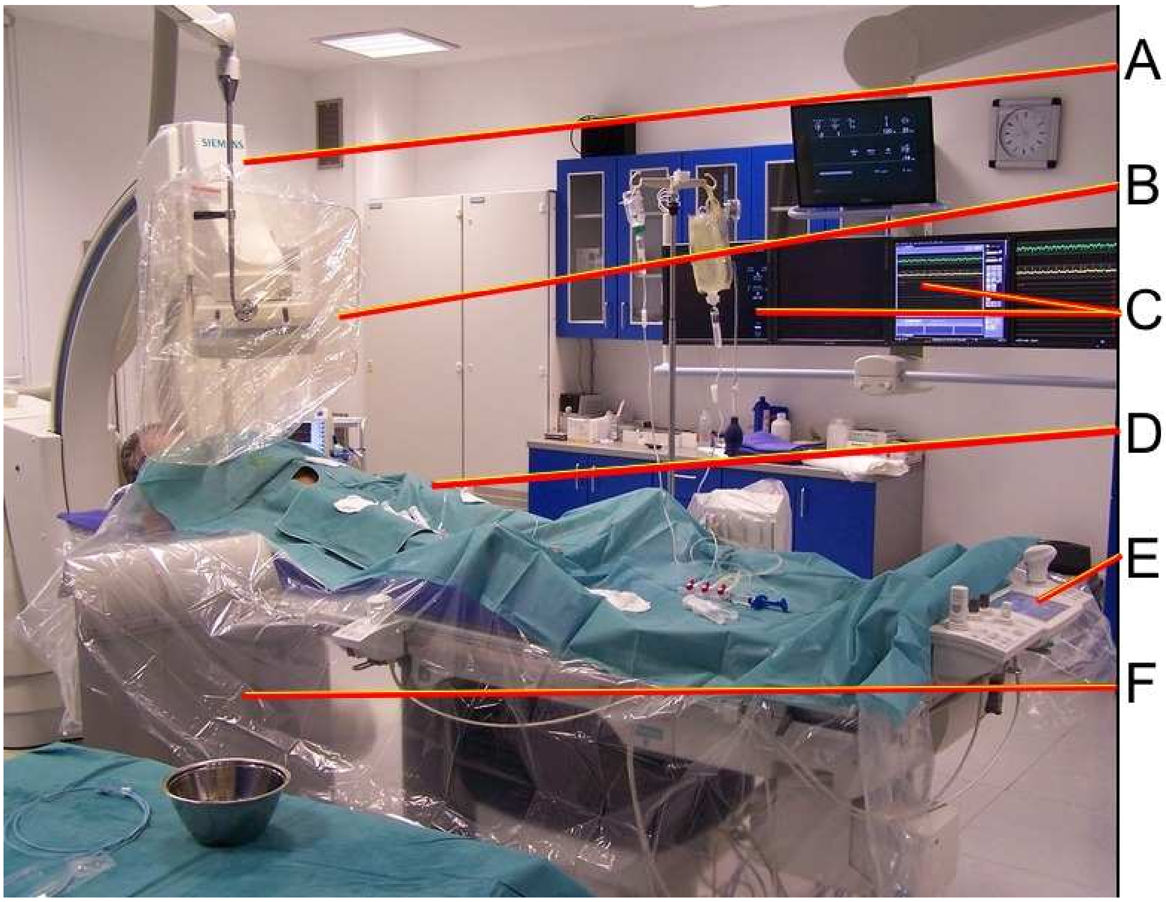

Figure 5. Patient position and shielding in the cath lab. Legend: A – digital flat panel detector mounted on C-arm; B – ceiling-mounted articulated protection screen; C – monitors; D – patient; E – C-arm and image contriol panel; F – table-side protective shielding.

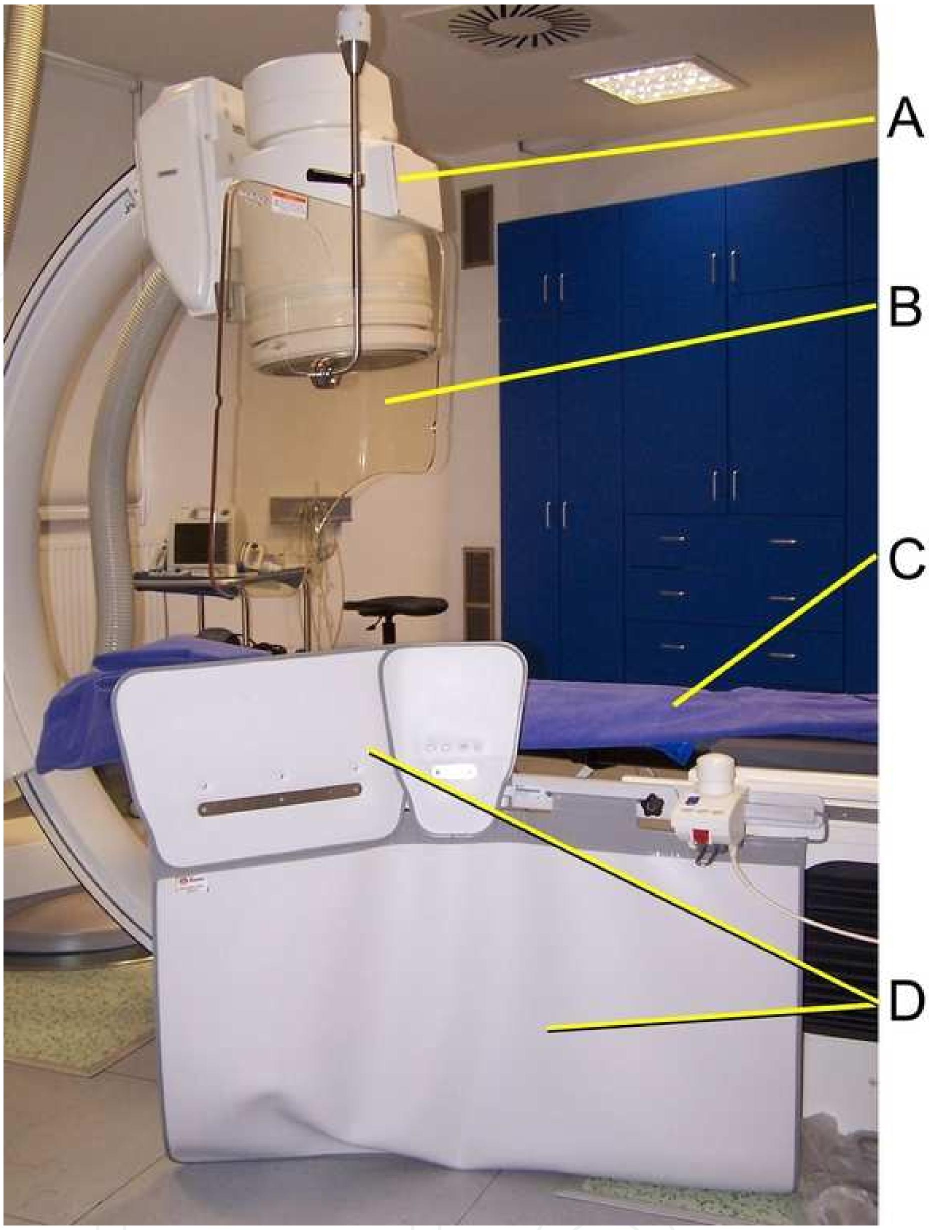

Figure 6. Radiation shields. Legend: A – image intensifier; B – Articulated, ceiling-mounted radiation protection screen; C – patient position; D – table-side shields.

The staff inside the cath lab must also wear the personal protection (fig. 7), which comes in several types and sizes. It is very important that one wears an adequate size protection garments. Firstly, lead apron should be worn. They come in different lead- or lead-equivalent thickness, and can weigh some 15 kg. It is advisable to wear the aprons which cover both the front and the back of the person. Because they may be heavy and put strain to the skeletal system, belts are used to take the weight off the shoulders. The minimum of protection is the equivalent of 0.5 mm of lead at the front. A two piece (blouse-plus-skirt design) is preferred by some operators. Another shield can be worn around the neck to protect the thyroid and neck tissues and organs (fig. 7). An additional small apron can be worn around the waist to

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increase the protection of the gonads (fig. 7). Since eyes can be affected when exposed to radiation over a prolonged period of time, it is advisable to wear leaded eyeglasses, or face-masks which are secured on the head (fig. 7). Protective eyewear must have at least the equivalent of protection of 0.5 mm of lead. Some recent investigations on the head exposure to radiation have resulted in a recommendation that leaded caps should also be worn.

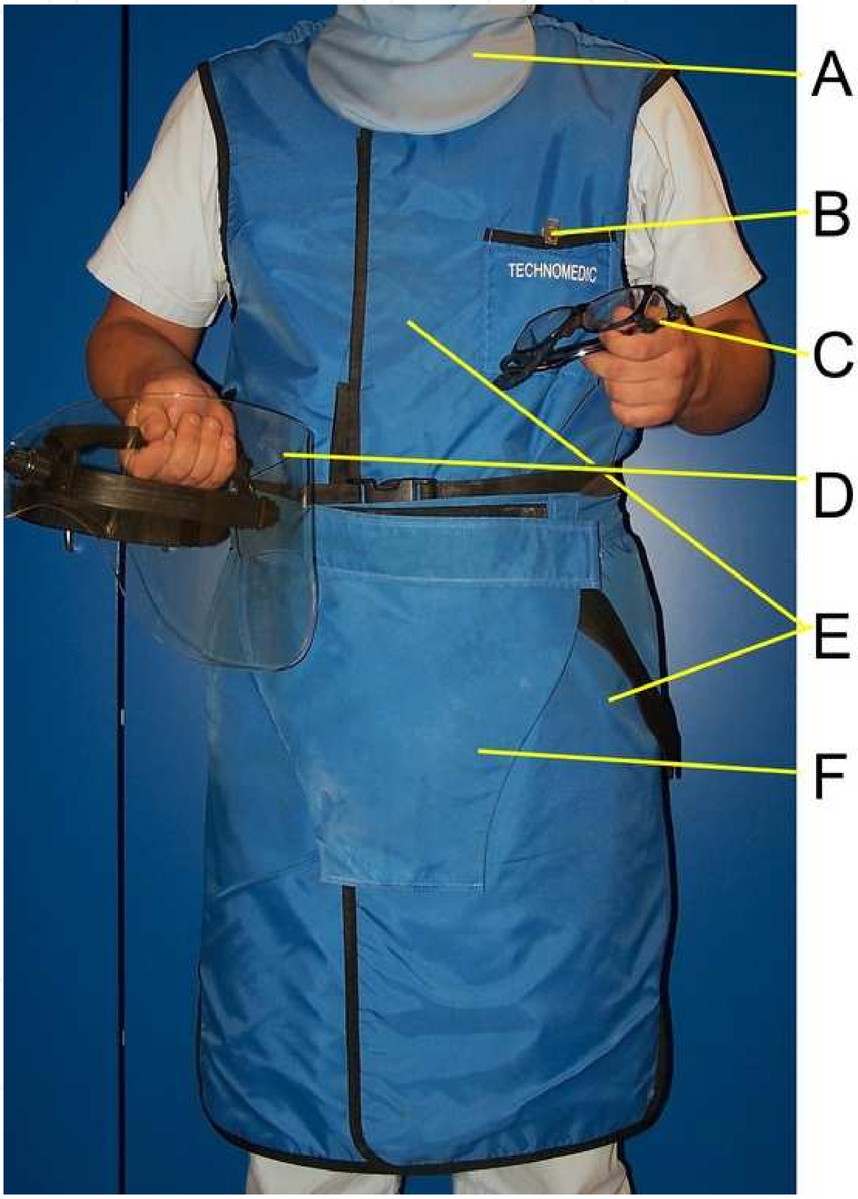

Figure 7. Personal protection for members of the staff in the cath lab. Legend: A –thyroid protection collar; B – outside personal dosimeter (in the pocket); C – protective eyeglasses; D – radiation panoramic full face mask for face shielding (preffered to eyeglasses); E – protective one-piece apron; F – additional protection for the gonads.

A cap with only 0.5 mm lead equivalence was proven to be more protective than a ceiling-mounted shield with 1.0 mm lead equivalence [21] This indicates that a significant amount of secondary scatter radiation, reflected from the walls of the cath lab, may reach the interventionist's head, despite the presence of a ceiling mounted lead glass shield, and this shield is actually designed to protect the operator's head from the primary scatter radiation from the patient. The annual head dose sustained by interventional cardiologists can be quite high, raising the issue of not only the cataract, but also brain tumors. The head dose may reach 60 mSv a year, and may in some cases exceed the occupational limit of 150 mSv a year recommended for the lens of the eye [22]. This information is the cause of the current consideration of the risks of radiation induced cataracts and malignancy, particularly brain cancer [23,24]. Primary scatter to the operator's unprotected head is highest for left anterior oblique (LAO) tube angulations [21]. However, some argue that a careful use of the lead glass shield provides similar protection of the operator's brain [20,25].

The exposure of the operator in general is higher when LAO projections are used, as opposed to RAO projections. The RAO positions are better regarding the operator dose, because the x-ray entrance point into the patient is kept away from the operator [3]. The RAO 90°, for example, exposes the interventionist to some three times less less scattered radiation than the usually used LAO 90° projection [26].

Even the line of interventonist's vision is important in this regard. The monitors in the cath lab are usually placed so that the patient can also follow the procedure, meaning that the monitors are to the interventionist's left front field of vision. For the operator, even leaning the head to the left increases the radiation exposure, and also the whole body posture is affected by this – the interventionist then stands closer to the x-ray tube, and to the source of scattered radiation. Just looking towards the tube exposes the lower parts of the face to levels 4–10 times greater than does looking rightwards [21]. Knowing that the monitor position typically determines the operator's predominant line of vision in interventional cardiology, it is advisable to place the monitors to the operator's right front side. By placing the monitors into the interventionist's right front part of the field of vision (fig. 5), radiation exposure of the interventonist's head can be dramatically reduced. This way, regardless of tube angulation, the lowest scatter towards the operator's head will occur in a line of vision toward the foot of the table. This means that in order to protect the eye lenses and the brain, interventional cardiologists should try to work with monitors positioned to the right [21]. Since the operator's hands might sometimes be directly under an x-ray beam, there are even sets of sterile leaded gloves (for single use, of course) that can be worn, although the material is obviously thicker than that used for normal sterile gloves, and the tactile feeling in the hands and at the operator's fingertips is not very precise.

The cath lab should be in a room of adequate size. Large rooms of some 60 m^2 are preferred not only because they are comfortable to work in, but also because in such rooms it is easy to employ the 'distance' and the 'shielding' principles of radiation protection [10]. A certain amount of space is also required for the ceiling-mounted radiation shields. Since the amount of radiation is reduced by the square distance from the source, in large rooms it is easy to distance and therefore protect oneself from radiation much better than in small rooms with limited space to move or stand. By staying inside the cath lab at the same time, assisting personnel can be readily available to attend the patient when needed.

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The equipment used in cardio-angiology is some of the most sophisticated and complex used in medicine today. It must be well-maintained and the users must be well trained in using it. As stated before, in all modern cardiology units, each fluoroscopic image is captured using a short pulse of x-ray beam. The pulse itself lasts for 3-10 ms. Longer pulses would appear blurry since structures observed in cardiology move. The pulse rate is identical to the image capture rate, and between pulses no radiation is being produced. At pulse rate of 30 images per second, the human eye perceives the series of fast changing images as a seemingly continuous motion. However, the amount of radiation at this pulse rate might be excessive. Reducing the pulse rate by half reduces (roughly by half) the amount of radiation to the exposed persons, and slightly affects the sequence quality, but usually not as much as to negatively affect the procedure. For large patients who require larger amounts of radiation to penetrate their bodies, reduction of pulse rate can mean the difference between no skin injury and the occurrence of radiation burns. Dose-rate control can also be achieved through modulating pulse width, tube current, beam energy, and filtration, but not all of these parameters can be controlled by the operator sometimes. The optimal control of these parameters means that the interventionist will choose the dose-rate mode which gives the smallest amount of radiation, while at the same time enabling adequate image quality.

A very important factor in determining the amount of radiation which will be used is the size of the patients. Smaller patients demand less radiation, and the image is brighter, crisper, and with better contrast. Bigger patients, however, demand larger amounts of radiation to obtain the same image quality. That amount is further increased with steeply angulated projections, so the operator must be aware of this while working with larger patients, and choose the projections wisely, to adequately display the region of interest while, at the same time, maintain the lowest radiation dose possible. When the lesions are difficult to treat, that prolongs the beam-on time and doses can be extremely high. Positioning the patient on cardio-angiographic table also plays a role in radiation exposure. To protect the patient against radiation burns, and oneself from scattered radiation, the operator is advised to keep the patient higher, farther away from the radiation source, and at the same time closer to the image receptor [5,6,7].

4.4. Radiation dose monitoring

Today, the modern cardio-angiographic devices are equipped with dose-monitoring systems which record the amount of radiation and calculate the exposure of the patient. There are also simpler methods, such as film-monitoring in which a film layer is positioned beneath the patient, roughly at the site of the beam entrance. The film is sensitive to radiation and becomes darker with higher doses. It is examined after the procedure (or during the procedure if necessary), and a simple device estimates the exposure based on the degree of the film darkening. This method is very good for estimating the skin exposure when the beam enters from posterior, but lacks preciseness if very angulated or lateral projections are used.

Automated devices for exposure measurement usually measure air kerma. The unit of measurement is Gy. It is the sum of initial kinetic energies of all charged particles liberated by the x-rays per mass of air. This measures the amount of radiation at a point in space and can assess the level of hazard at the specified location. Most modern devices used in interventional cardiology have a built-in monitor of total accumulation of air kerma at a reference point, and this point in interventional cardiology approximates the position of the skin where the beam enters the patient. It adds up the radiation from all projections, making it in this sense more convenient than the film monitor, but it approximates, so the true result might be different from the measured value. Some machines have the possibility to measure kerma-area product and dose-area product. The logic of these devices is based on the fact that the beam area increases with the distance from the source, and the air kerma decreases. Theoretically, the product of these values is the same at all positions along the beam. This is primarily a quality control measurement, and if one wants to calculate the dose to the patient, usually a medical physicist must be consulted, because such calculations can be quite complicated.

As for the staff, radiation monitors must be worn at all times during the procedure. This way the exposure of the staff can be measured. It is necessary for interventional cardiologists and other personnel employed in the cath lab to wear personal radiation exposure monitors (dosimeters) on a regular basis, although sometimes this is not the case. Sometimes dosimeters are not worn because of a lack of awareness of risks associated with radiation and/or lack of education in radiation protection [27]. In some institutions or countries, regulatory bodies demand that the monitors are placed outside the protective aprons, while others demand that they must be worn underneath the protection garments. In some hospitals (as is the case in the hospital in which the author works), two monitors must be worn per person: one on the outside, and the other one beneath the protective apron. The one outside records the exposure of the unprotected areas (fig. 7). If only that one is worn, it can be approximated that the dose underneath 0.5 mm of lead equivalent is 0.5% of the dose measured on the outside monitor. Wearing only under-the-apron monitor may give the operator a false sense of security and lead to potentially heavy exposure of the unprotected body parts. Also, the monitoring of the exposure at the hands and legs/feet should be considered, at least periodically. Beside wearing the monitors, the staff working inside the radiation environment must undergo periodical clinical examinations to evaluate the state of their skin, to detect vision impairment, to do blood tests, and to check for chromosomal abnormalities, and possibly other diagnostic measures, as defined by the responsible regulatory bodies. Sometimes, if the doses of radiation exposure found in an employee are larger than recommended, the employee will be ordered to be removed from the radiation environment, temporarily or permanently.

5. Pregnancy and x-ray radiation in the cath lab

There are two ways in which the pregnancy can affect radiologic procedures in a cath lab: either one of the staff is pregnant, or the patient is pregnant. Both situations warrant a careful approach and need to be mentioned.

If a member of the staff is pregnant, different regulatory bodies define different forms of radiologic protection for the woman and the fetus. In some countries, the recommendations are that the fetus must be protected, while not interfering with the future mother's ability to do her job. The employees, both men and women, must be introduced to radiation safety measures in connection with reproductive issues. Usually, there is also a recommendation that all female employees of childbearing potential carry a whole-body dosimeter on the outside of the protective apron, as well as a dosimeter worn under the apron, at the abdominal level. The readings on these dosimeters must not exceed 0.25 mGy per month, thus ensuring that the conceptus receives less than a half of a maximum allowed dose recommended by the professional agencies (which is 0.5 mGy). A pregnant employee must be provided with an option to wear an additional pelvic shield of 0.25 to 0.5 mm of lead equivalent material. The employee should also be provided with duties involving less radiation exposure, if at all possible. In some countries, as is the case in the author's country, the pregnant employee who works in a medical radiation environment has the right to start pregnancy-leave at the very beginning of the pregnancy, and continue with it up to one year postpartum. It is the author's firm belief that all pregnant employees must be given an option to take pregnancy-leave as soon as they learn they are pregnant, so no unnecessary radiation risks, small as they might be, are imposed on the fetus and the pregnant mother-to-be.

When there is a pregnant patient in the cath lab, it is usually a patient with an acute coronary syndrome (ACS). Although pregnant women rarely have ACS, this is possible and the staff must be prepared for such an event. With general population, percutaneous coronary intervention (PCI) is the preferred treatment modality for an acute myocardial infarction. On the other hand, PCI in pregnancy includes the exposure of fetus to ionizing radiation. High doses of radiation carry the risk of a spontaneous abortion, fetal organ deformities, fetal mental retardation and a higher incidence of childhood cancer. However, radiation doses received by fetus during a PCI on a pregnant woman are completely acceptable and PCI can and must be performed in a pregnant woman with an ACS. Before the introduction of the practice of ACS treatment by using PCI, ACS mortality in pregnancy was as high as 20% [28]. Today, by using PCI in the treatment of ACS, the mortality from ACS in pregnancy is reduced to only 5% [29]. During the invasive cardiologic procedures, the x-ray beam is directed to the patient's chest. Some of the radiation does penetrate even to the fetus, and a part of it is scattered radiation from the mother's body. Contemporary cardio-angiography machines, with excellent beam collimation and a precise beam direction, have very little primary beam dissipation. Since that kind of radiation is still theoretically possible, it is mandatory to protect the pregnant patient's abdomen with protective leaded aprons. The mean exposure of a fetus during a PCI procedure is 0.02 mSv, and in very difficult and time-consuming procedures can reach up to 0.1 mSv. These doses are acceptable, and are even relatively small when compared to computer tomography (CT) scan of the abdomen (8 mSv on average, to a maximum of 49 mSv), pelvic CT scan (25 mSv on average, to a maximum of 79 mSv), abdominal radiography (1.4 mSv on average, with a maximum of up to 4.2 mSv), or even a CT-scan of the thorax (0.06 mSv on average, to a maximum of 0.96 mSv). Doses over 50-100 mSv increase the incidence of fetal malformation. The radiation which is scattered from the directly irradiated body part reaches the fetus, but this is only a small fraction of the radiation dose reaching the pregnant patient's thorax [5]. Although it protects from a direct beam, the leaded apron at the patient's abdomen will not protect the fetus from the scattered radiation within the patient's (pregnant woman's) body. Taken into account the spectre of causes of an acute myocardial infarction during pregnancy, PCI will in most cases be the treatment of choice during pregnancy. Not only that it treats the thromboembolic processes, but their causes can be treated also, namely the coronary dissection, which is a disproportionally common cause of ACS in pregnancy, probably because of the alterations in the connective tissue structure (including that within the coronary artery walls) mediated by pregnancy hormones. Once again, PCI is considered to be relatively safe during pregnancy, both for the pregnant patient and for the fetus and it must be employed as the first line of treatment for ACS in pregnancy because it dramatically reduces ACS mortality for pregnant women.

6. Conclusion

In conclusion, although the discovery of the x-ray radiation is more than 100 years old, the x-ray technology is developing as fast as ever. As much as we need to learn about its usefulness and the different forms of its application, we must always be aware of its dangers, risks, and limitations, and use it with care and adequately protect ourselves and our patients.

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