Chapter 3

Medical Imaging and Image-Guided Interventions

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Additional information is available at the end of the chapter

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Abstract

The discovery of X-rays at the end of the nineteenth century is one of the most important discoveries that changed the human being life in all fields and applications. Since that date, X-ray systems are developed rapidly, and still new applications are emerging in medical, agricultural, and industrial fields. This chapter provides sufficient historical background for X-ray production and image acquisition techniques. It covers also fluoroscopic equipment and radiation dosimetry and protection techniques in detail. Image-guided intervention is here to stay. Thus, suitable radiation protection measures are required to minimize the risk to patients and staff to its minimal level without affecting the outcome of the procedures.

Keywords: medical imaging, X-ray, radiation risk, radiobiological effect, skin injury, interventional radiology

1. Background

Since the discovery of X-rays accidentally by Professor Wilhelm Roentgen (from March 27, 1845 to February 10, 1923), a German scientist, Rector of Wurzburg University on Friday, November 8, 1895, a huge development was occurred in the technology of X-ray machines and its applications [1]. He provisionally called these as X-rays. Afterward, he and other scientists performed systemic scientific research to define the newly discovered X-rays. Few months later, in February 1896, in recognition of his discovery, the scientific community named these X-rays as Roentgen rays [2]. Later in 1901, Roentgen awarded the first Nobel Prize in Physics in recognition of his discovery. Recently in 2004, the International Union of Pure and Applied Chemistry, in honor of Roentgen, named the highly radioactive element with atomic number 111 Roentgenium ($^{280}Rg_{111}$) (**Figure 1**) [6].

Figure 1. William Roentgen.

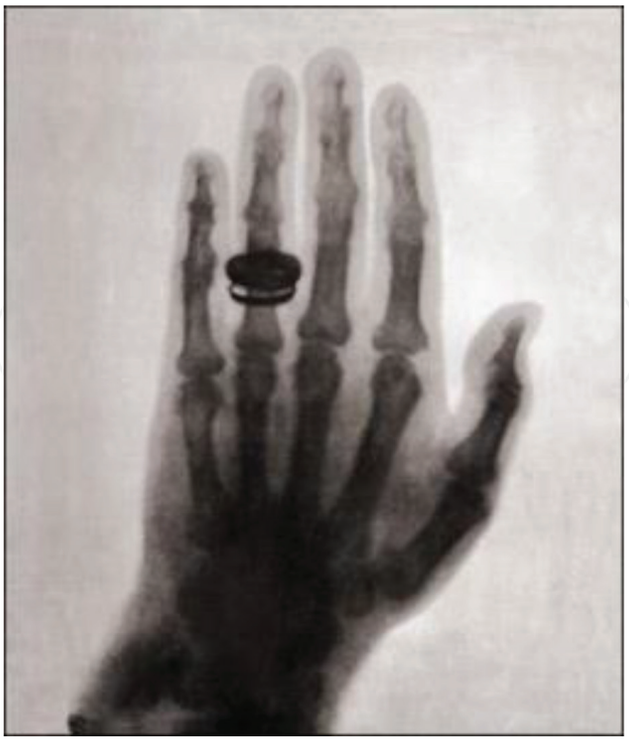

Figure 2. The first X-ray image (left hand of Bertha Roentgen).

The first X-ray image of a human was the hand of Wilhelm Roentgen's wife Bertha Roentgen on December 22, 1895. This opened the door for medical applications of X-rays (**Figure 2**). At that time, X-rays were only known as a form of electromagnetic radiation (photons) with short wavelength ranged from 10^{-2} to 10^{-9} nanometer.

2. Characteristics of X-rays

Other main characteristics were revealed including:

1. Penetration: X-rays can penetrate most objects, and the penetration ability depends on photon energy (tube voltage (kVp)) and the object medium characteristics (thickness, density and the atomic number). The X-ray penetration ability is inversely dependent on medium characteristics.
2. Ionization and excitation of atoms: X-rays have sufficient energy to ionize air, i.e., eject electron from an atom, producing positive ion and free electron. As hydrogen is the atom with a minimal binding energy (−13.5 eV), which considered the threshold energy between ionizing and nonionizing radiation, photons of energy higher than 13.5 eV are ionizing radiation. Excitation occurs when the orbital electron absorbed energy less that its binding energy, which resulted in raising electrons to higher energy levels. Ionization of gas is the oldest method of radiation detection and dosimetry.
3. Fluorescence: X-rays can cause certain materials such as calcium tungstate to emit visible light. This is one of the major characteristics of X-rays used in medical imaging, which resulted in reduction of patient radiation dose by using intensifying screens and conversion of X-rays to visible light. Fluoroscopy is used to obtain dynamic images for diagnostic and/or therapeutic purposes.
4. Photographic effect: X-rays can produce a silver ion (Ag^+) and an electron when they interact with silver bromide (AgBr) or silver iodide (AgI) (photosensitive materials which are sensitive to X-rays and light). This effect is invisible (latent imaging) and can be converted to visible image via development or processing. X-rays have different shades of gray based on the X-ray beam absorption in the body. The conventional X-ray film consists of 98% AgBr and 2% AgI.
5. Chemical effect: X-rays can produce chemical alterations in certain materials. This chemical change in living organism can lead to biological effect (see list 7). The accurate quantification of the chemical change in the absorbing material enabled scientists to measure the absolute radiation dose (Fricke dosimeter).
6. Thermal effects: when a medium is exposed to X-rays, tiny amount of energy is converted to heat, and thus increases the medium temperature. If a suitable calorimeter is used, the absolute absorbed dose can be estimated in relation to medium temperature.
7. Biological effect: One of the major effects of radiation is the ability to cause damage to cells, organs, or organisms. Thus, patients, staff, and public protection are major concerns in medical imaging. On the other hand, these biological effects are used to destroy cancerous cells and cure patients with fatal diseases.

8. Medical imaging: radiographic imaging is used to extract patients' anatomical and physiological data in order to diagnose a clinical condition. Image formation consists of the following stages:

    1. X-ray passes through the patient during imaging procedures.

    2. As X-rays penetrate through the body tissues, it become modified and each part of the beam is attenuated in a degree that depends on:

        a. the tissue type;

        b. the intensity of the beam; and

        c. thickness of the tissue.

    3. A suitable image receptor receives the signal and creates radiograph with different levels of gray scales according to the tissue attenuation.

3. Image-guided interventions

Interventional radiology is a newly emerged branch from radiology using fluoroscopic guidance to perform complex procedure noninvasively. Nowadays, many imaging modalities are used in the field of image-guided interventions. These imaging technologies include, in addition to planar fluoroscopy, CT, MRI, and ultrasound. The image-guided intervention techniques expanded rapidly due to its numerous advantages including local anesthesia and low rate of mortality and morbidity (short stay at hospital).

3.1. Fluoroscopy

Fluoroscopy, or real-time imaging, is an imaging technique that produces dynamic images at low tube current range from 0.5 to 5.0 mA for longtime intervals, resulting in dynamic images with lesser image quality. The fluoroscopy played a fundamental role in emergence of interventional radiology since its introduction by Thomas Edison (1847–1931) in May, 1896, just an year after the discovery of X-rays. The early fluoroscope composed of fluorescent screen (zinc-cadmium sulfide) placed over the patient's body between the patient and radiologist (**Figure 3**) at complete darkness, and the radiologist looked directly at the screen. Dark adaptation was required from 10 to 30 minutes by wearing red goggles to enhance viewing.

3.2. Contrast medium

From the early days of medical application of X-rays, practitioners noticed the need of soft tissue and blood vessels imaging. Thus, many experiments were conducted in order to alter the absorption characteristic (atomic number) of the tissue in relation to their adjacent structures (soft tissue effective atomic number ≈ 7.4). Thus, negative contrast media (air) and positive contrast media were developed for gastrointestinal tract in 1910, for oral and rectal administration

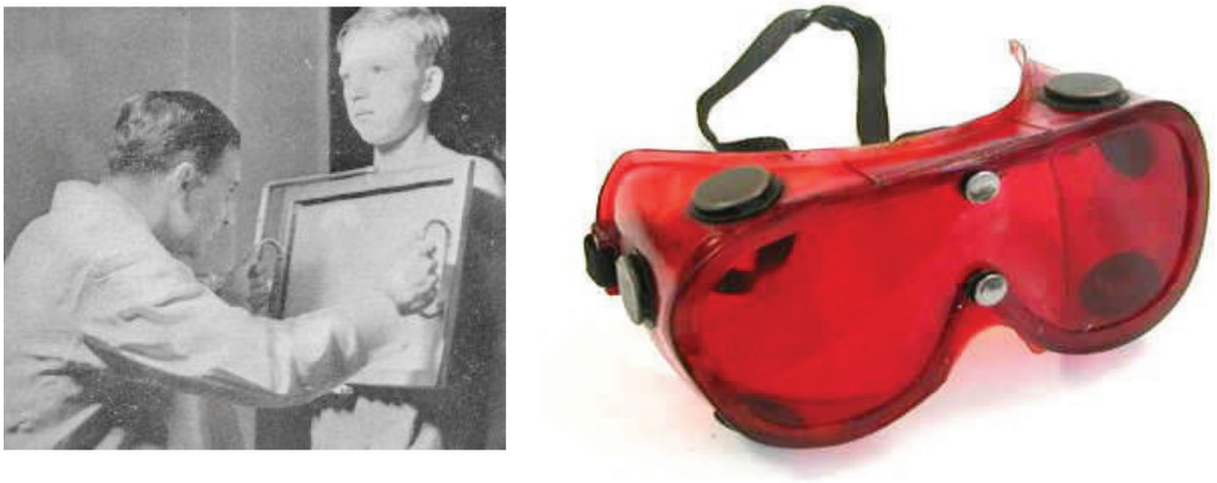

Figure 3. (A) Radiologist using a fluoroscope during an examination; and (B) red goggles.

exclusively (barium sulfate ($BaSO_4$), with effective atomic number 56), and gastrografin (Diatrizoate Meglumine and Diatrizoate Sodium Solution, effective atomic number 53), which is an iodinated soluble contrast medium, was developed in 1954. For cardiovascular system, urografin (amidotrizoate meglumine; sodium amidotrizoate ($C_{11}H_9I_3N_2O_4$)) was developed [2].

Afterward, the clinical experiments on cardiac catheterization and angiography progressed extensively, and in 1956, Forssman and Cournand received the Nobel Prize in physiology and medicine for their efforts in development of cardiac catheterization [3].

The image-guided intervention was started as a diagnostic technique, but due to the development of recent imaging technology such as CT angiography and magnetic resonance angiography (MRA), it becomes a pure therapeutic technique. Image-guided intervention is performed usually under fluoroscopic guidance. However due to the development of other imaging modalities such as CT, MRI, and ultrasound, these techniques are progressing with some drawbacks that include radiation risk in CT imaging, metallic surgical tools as a limitation for MRI application in interventional procedures, and ultrasound poor image quality [4]. In addition to that, a combination of fluoroscopy with endoscopy provided also excellent approach to treat many clinical conditions.

4. Image-guided intervention instrumentation

Fluoroscopic equipment was developed in 1896 by Thomas Edison. At that time, very simple instruments were used without any consideration of radiation protection for patients and staff (**Figure 3B**). Since that date, fluoroscopy equipment technology developed rapidly, and new applications are emerging continuously (**Figure 3A**; old practice in fluoroscopy).

4.1. Types of fluoroscopic equipment

Fluoroscopic equipment is classified into two types:

4.1.1. General purpose fluoroscopy X-ray machine

The first type is a general purpose fluoroscopy X-ray machine (permanently fixed fluoroscopic unit) which is usually installed at radiology departments or other interventional radiology departments such as orthopedic. There are two configurations of permanent units: fluoroscopic unit with under couch X-ray tube and over couch image intensifier or vice versa. Over couch X-ray unit has some advantages including better flexibility in patient positioning, possibility to use the same X-ray tube for radiography imaging with stand Bucky, and possibility to adjust source-skin distance. However, over couch X-ray units are not recommended for interventional procedures because staff exposure increases five to six times compared with under couch X-ray tube and over couch image intensifier configuration [5]. The minimum source (X-ray tube) to skin distance must be at least 30.5 cm away from the surface of skin. Modern C arm machine has mobile spacer cones to maintain the correct distance. Operator can remove the cone temporarily if it interferes with the procedure in under couch position. The other configuration is C arm unit. C arm is an X-ray unit where the image intensifier (flat-panel detector (FPD)) and X-ray tube are at two ends of the letter C as illustrated in **Figures 4** and **5**. C arm equipped with FPD, which costs three times, has the capability to produce better image quality compared with image intensifier. C arm is utilized to provide more wherever greater flexibility in image acquisition at different projections (views). The machine is used to perform minimally invasive procedures such as cardiac catheterization, angiography, orthopedic, gastroenterology and therapeutic interventional procedures. Recent development in imaging technology enables C arm system to obtain fluoroscopy images and 3D cone-beam CT (CBCT) images. Vascular studies are usually performed in fixed fluoroscopy unit. A C-arm X-ray machine is preferable because it can be rotated rather than the patient during the procedure. Some fluoroscopic X-ray systems are equipped with two radiation sources, which enable reduction of the number of injections of contrast required.

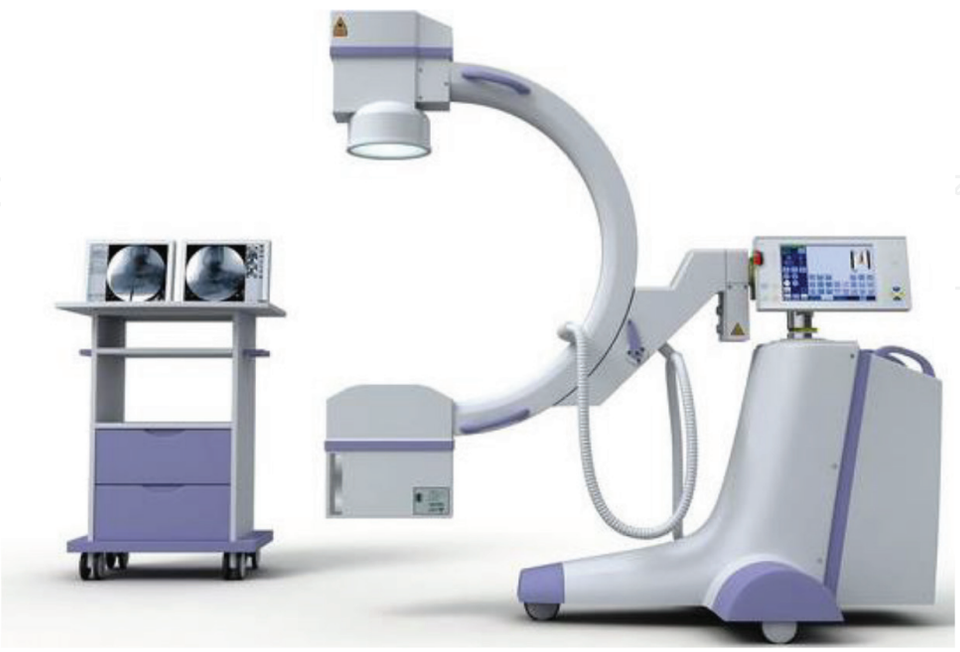

Figure 4. Modern C arm X-ray machine (large).

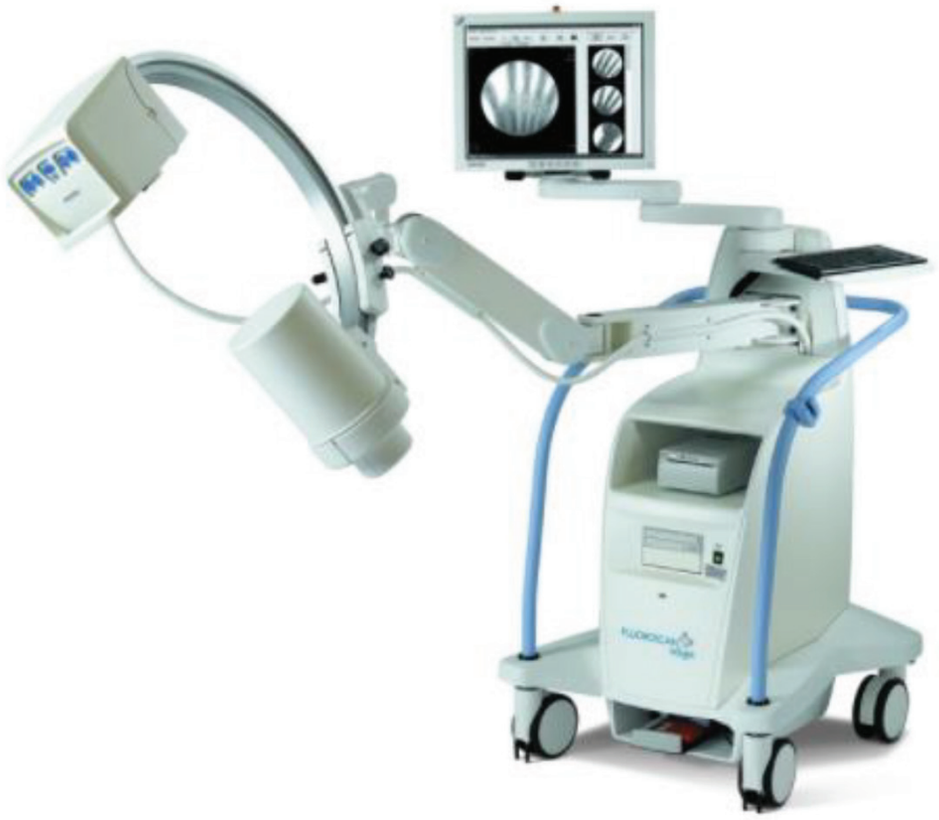

Figure 5. Mini C arm X-ray machine used for pediatric and extremities (1/10th of large C arm dose).

4.1.2. Mobile C arm

The second type is mobile C arm, which is more convenient and can be moved from one place to another according to the need of the operator, and image can be transferred via Bluetooth in modern equipment to the printer. Thus, C arm is commonly used in operation rooms.

C arm has two types:

a. large C arm; and

b. mini C arm.

Mini C arms are small fluoroscopes used mainly in orthopedic procedures (extremities) and pediatric procedures. Operators can control the fluoroscopic unit from the control panel and inside the room with a foot pedal. The image quality is lower in fluoroscopy compared with radiography due to low tube current used in the first one. The dose is lowered by 45–60% during fluoroscopy image acquisition compared with radiography [6]. Auto fluoroscopy is an option that provides an optimum tube current (mA) to provide sufficient image quality. Acceding to the international recommendations, pulsed fluoroscopy intermittent pulses (from 2 to 30 times per second) are used to reduce patient doses during the procedures by 50% of its initial value while maintaining image quality. Digital fluoroscopic units are capable to store images from the detector (fluorography) and last image hold (the last frame acquired is left on the monitor after the X-ray beam is switched off).

5. CT fluoroscopy (CTF)

The substantial advances in CT technology have led to development in CT fluoroscopy in 1993, which allows fluoroscopic image acquisition with high image quality compared to conventional fluoroscopy [7]. This development in CT technology (slip ring technology in 1980s and X-ray tubes with high anode heat storage capacity up to 30 million heat units (MHU) or 22,000 kJ) and high speed processing units and advances in reconstruction software, enabled acquisition of high image quality in a short time with lower radiation dose) [8]. CT fluoroscopy becomes popular in image-guided intervention despite of the concern regarding radiation risks due to its advantages compared with conventional fluoroscopy and surgery. CT fluoroscopy is very valuable biopsy for deep structures, stent placement, and lesion drainage. CT fluoroscopy is usually performed using the following exposure parameters: 120 kVp, 30–90 mA, scan time range from 0.5 to 1.0 s, and fluoroscopic images displayed in certain time interval range between 3 s^{-1} and `12 s^{-1} [9].

6. Radiation doses from image-guided intervention procedure

Fluoroscopy screening exposure time during image-guided intervention depends upon the type of the procedure and operator skills and X-ray machine technology and machine set up. Different procedures have different screening times. Usually, cardiology intervention procedure requires longer screening time compared with orthopedic procedures.

6.1. Tissue reaction during interventional procedure

When X-ray radiation penetrates a tissue or a medium, it deposits energy. The energy absorbed from exposure to radiation is termed a dose. Certain interventional procedure requires prolonged exposure time. These procedures are:

a. Vascular embolization

b. Stent and filter placement

c. Thrombolytic and fibrinolytic procedures

d. Percutaneous transhepatic cholangiography

e. Radio-frequency cardiac catheter ablation

f. Percutaneous transluminal angioplasty (coronary and other vessels)

g. Endoscopic retrograde cholangiopancreatography

h. Transjugular intrahepatic portosystemic shunt placement

i. Percutaneous nephrostomy

j. Biliary drainage or urinary or biliary stone removal

6.2. Tissue reaction in image-guided intervention

The dose rate during fluoroscopic-guided intervention ranged between 0.02 and 0.05 Gy/minute [10]. It was estimated that the mean patient dose for cardiac catheterization is 2.5 Gy, and during percutaneous interventions, the dose may reach 6.4 Gy per procedures, which is higher than the erythema dose [11]. Erythema occurs due to accumulative patient doses from multiple procedures, each of which is individually insufficient to cause injury. Most of the patients require more than one procedure within a short time such as patients with ischemic heart diseases (IHD). **Table 1** shows the tissue reaction threshold during image-guided intervention procedures using fluoroscopy. **Table 2** illustrates the biological effect on patients after exposure to certain doses. **Figures 6–11** show radiation-induced skin injuries due to prolonged irradiation.

Deterministic effect	Typical threshold dose (Gy)*	Time of onset*
Early transient erythema	2	~2–24 hours
Temporary epilation	3	~3 weeks
Main erythema	6	~10 days
Permanent epilation	7	~3 weeks
Invasive fibrosis	10	—
Dry desquamation	14	~4 weeks
Late erythema	15	~8–10 weeks
Moist desquamation	18	~4 weeks
Ischemic dermal necrosis	18	>10 weeks
Secondary ulceration	24	> 6 weeks
Dermal atrophy (1st phase)	10	>52 weeks
Telangiectasia	10	> 52 weeks
Dermal necrosis (delayed)	>12	>52 weeks

*actual skin dose not entrance surface air kerma

Table 1. Tissue reaction effects of acute radiation exposure.

Radiation equivalent dose (Sv)	Subsequent effect
0.25	Blood changes (e.g., measurable hematologic depression, decrease in the number of lymphocytes present in the circulating blood)
1.5	Nausea, diarrhea
2.0	Erythema (diffuse redness over an area of skin after irradiation)
2.5	If dose is administered to gonads, temporary sterility
3.0	50% chance of death
6.0	Death

Table 2. Biological effects of radiation [11, 12].

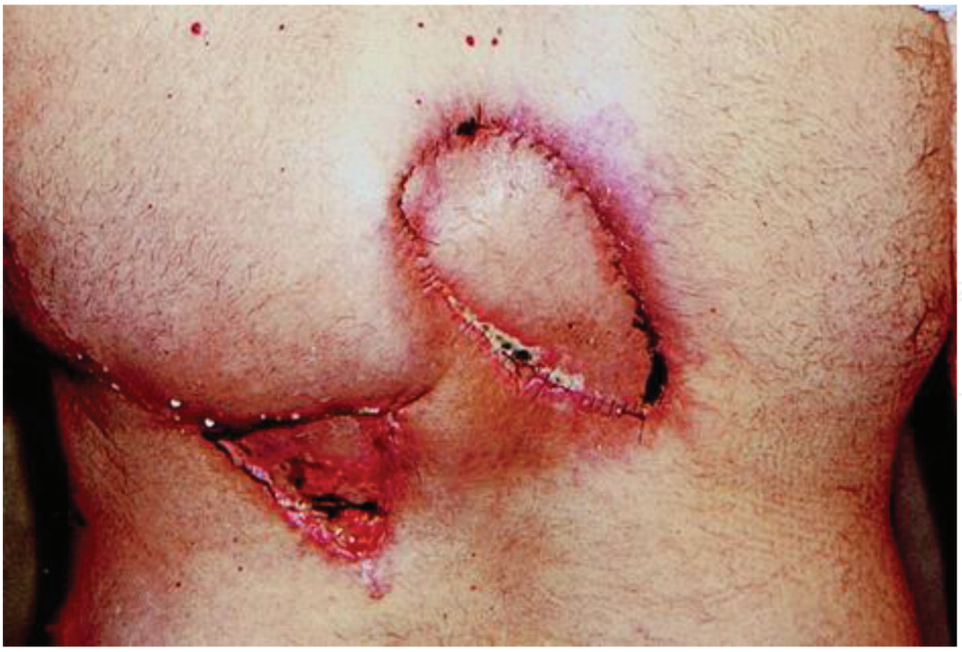

Figure 6. Tissue reaction effect for a 49-year-old patient who underwent two transjugular intrahepatic portosystemic shunt (TIPS) placements and one attempted TIPS placement within a week [12].

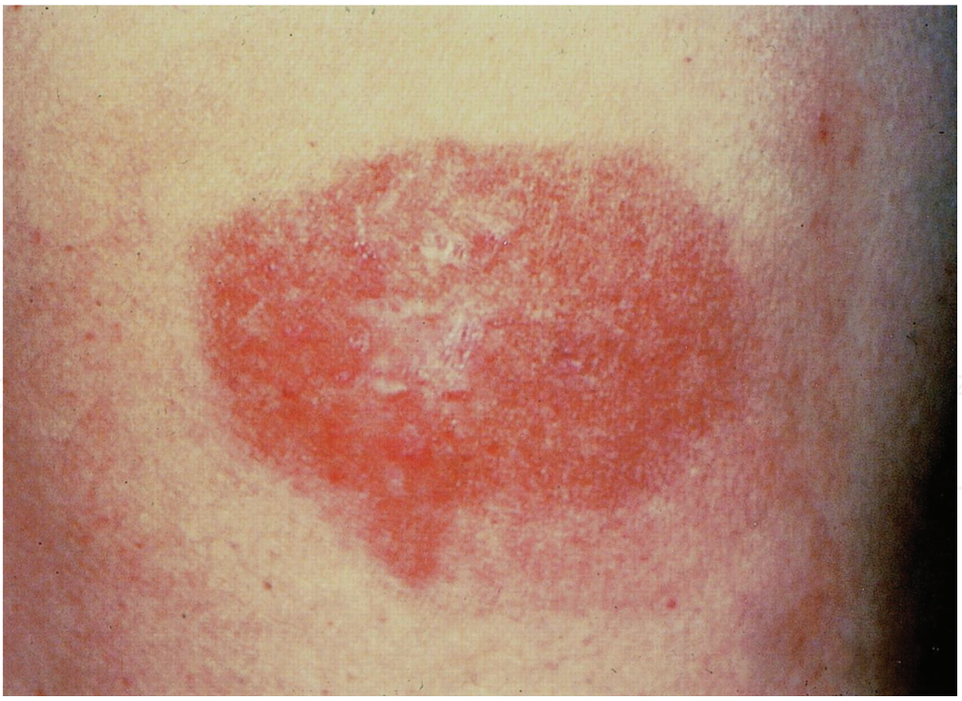

Figure 7. Photograph of right posterolateral chest wall at 10 weeks after PTCA for a 56-year-old man with obstructing lesion of right coronary artery [12].

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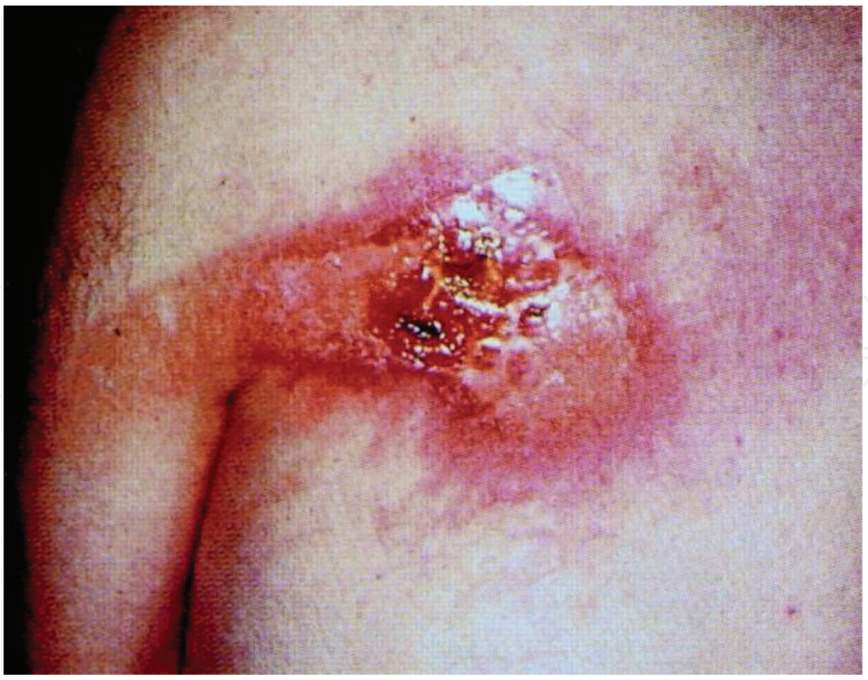

Figure 8. Secondary ulceration after two months for a 69-year-old patient underwent two angioplasties of left coronary artery within 30 hr [12].

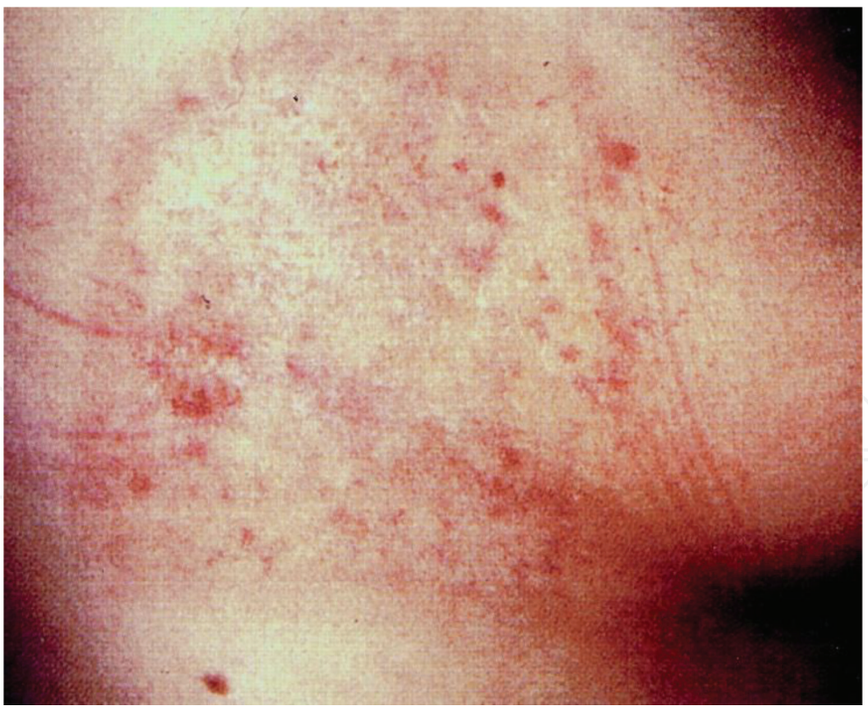

Figure 9. Skin telangiectasia after 2 years for a 17-year-old patient underwent two cardiac ablations procedures within 13 month [12].

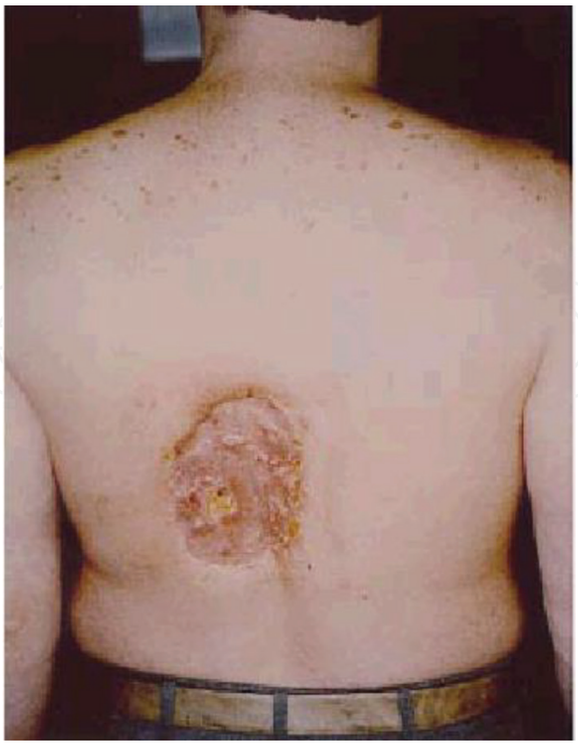

Figure 10. Radiation wound 22 months after angioplasty procedure [15].

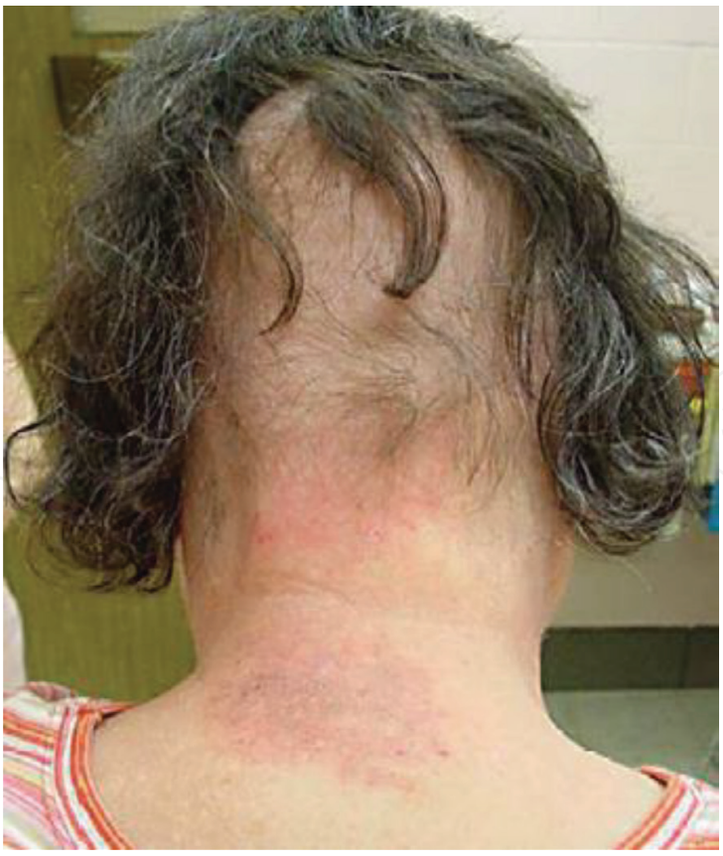

Figure 11. Radiation injury in a 60-year-old woman subsequent to successful neurointerventional procedure for the treatment of acute stroke [11].

7. Patient doses measurement

When performing radiographic examinations, patient doses can be evaluated as entrance surface air kerma (ESAK), the dose administered to the skin, where an X-ray beam enters the body, which includes the incident air kerma and backscattered radiation from exposed tissue. ESAK is measured using dosimeters or through calculations from the applied exposure factors and measurements of X-ray tube output [13]. Another method is the kerma-area product (KAP), defined as the product of the dose in air (air kerma) within the X-ray beam and the beam area, which enables the measurement of overall radiation entering a patient. KAP can be measured using an ionization chamber fitted to the X-ray tube. The two methods can be applied to calculate and monitor radiation doses for the various radiological examinations compared to guidance and diagnostic reference levels (DRLs). Many research bodies have been active in the area of DRL, including the International Atomic Energy Authority (IAEA) and International Commission on Radiological Protection (ICRP). The objective of DRLs is to aid in preventing the administration of unnecessary radiation doses to patients that do not support the clinical purpose of a radiographic exam. Each X-ray facility should set up DRLs following international guidelines with regular assessments and applications of corrective action in cases where these levels are exceeded.

8. Quality assurance

Quality assurance in medical imaging intends to ensure the consistent provision of prompt and accurate diagnosis of patients with minimum radiation exposure to patient and staff and to be cost-effective.

8.1. Image quality

Image quality, which is defined as the exactness of representation of patient anatomy, is affected by many factors including organ of interest, imaging modality, patient, and imaging modality characteristics. Images in clinical environment are evaluated subjectively by operators (radiography technologist or radiologists) or objectively (independently of an observer opinion) by measuring certain parameters. These parameters include brightness, contrast resolution, special resolution distortion, artifact, and noise, as illustrated in **Table 3**.

Tables 4 and **5** show factors affecting patient doses during interventional procedures. Patient dose depends, among other factors, on X-ray unit technology, proper equipment design and utilization, proper set up of equipment parameters, and operator skills.

Optimization in diagnostic radiology signifies balancing diagnostic information (image quality) and patient dosage through identifying an image acquisition technique that maximizes the perceived information content and minimizes radiation risk or keeps it at a reasonably low level (ALARA).

The factors that affect patient dose and image quality and form the backbone of optimization in diagnostic radiology fall into three categories: facilities and equipment, operational conditions, and application factors.

Image quality factor	Definition/controlling factor(s)
Brightness	• **Definition:** the intensity of light representing image pixels on the monitor • **Controlling factors:** the optimal digital image brightness is influenced by a wide range of exposure factors and controlled by processing software through digital processing algorithms. The operator can apply post processing algorithms to modify pixel values of the image. Windowing is used to manipulate and adjust the brightness of the digital image after exposure by altering the window level (WL) within a certain range. Smoothing and edge enhancement of the image can also be increased for better brightness.
Contrast	• **Definition:** the difference in brightness between light and dark areas of an image • **Controlling factors:** control of scatter radiation is an important factor in obtaining the appropriate image contrast through correct use of grid, close collimation, and selection of optimal kVp • Radiographic contrast is affected by the digital processing computer through application of predetermined algorithms. Through post processing, the user can manipulate the contrast of the digital image
Resolution	• **Definition:** the recorded sharpness or detail of structures on the image • **Controlling factors:** traditional factors as for film screen imaging besides acquisition pixel size inherent to the digital imaging detector and display matrix. Perceived resolution of the image dependent on the display capabilities of the monitor
Distortion	• **Definition:** the misrepresentation of an object size or shape as projected onto recording media • **Controlling factors:** as for film screen imaging, the factors that affect distortion are the source image receptor distance (SID), object image receptor distance (OID), object image receptor alignment, and central ray alignment (**Table 1**)
Artifact	• **Definition:** EI is a measure of the amount of exposure received by the image receptor • **Controlling factors:** EI is dependent on mAs, total detector area irradiated, and beam attenuation. The exposure index is indicative of image quality. Equipment manufacturers provide a recommended EI range for optimal image quality
Noise	• **Definition:** random disturbance that obscures or reduces clarity. • **Controlling factors:** technologists must ensure that exposure factors used for examination are not beyond those required for the projection by checking the exposure index to avoid needless overexposure of the patient. On the other hand, scattered radiation is a potential source of noise that can be controlled by the use of grids and correct collimation. Image noise may also be related to the electronic system, nonuniformity of the image receptor, or power fluctuations. • Increasing input doses • Frame averaging—smooth by adding successive images at the expense of temporal resolution

Table 3. Image quality factors and their controlling/influencing factors in DR.

8.2. Establishment of diagnostic reference levels

To improve the optimization in diagnostic procedures, the ICRP recommends the use of diagnostic reference levels (DRLs) to ensure that the doses do not deviate significantly from internationally reported levels to those achieved at peer departments for that procedure unless

Parameter	Control of parameter	Management
Patient size	Not controllable	Increase the exposure parameters
Type of procedure and pathology	Not controllable	Therapeutic procedures require more fluoroscopic time than diagnostic procedures
Patient setup	Controllable	Accurate patient positioning before the procedure reduces the need for patient positing using fluoroscopy
Patient preparation and communication	Controllable	Good patient communication increases patient cooperation and reduces the possibility of patient movement during the exposure and hence minimizes the possibility of image blurring

Table 4. Patient related factors affecting patient radiation doses.

Parameter	Control of parameter	Management
Experience	Not controllable	Increase the exposure parameters
Radiation dose monitoring	Not controllable	Therapeutic procedures require more fluoroscopic time than diagnostic procedures
Dose reference levels	Controllable	DRL could be used to improve patient dose management in order to avoid unnecessary radiation exposure
Use of specified protocol	Controllable	Good patient communication increases patient cooperation and reduces the possibility of patient movement during the exposure and hence minimizes the possibility of image blurring
Collimation	Controllable	Proper collimation of radiation to the region of interest reduces patient and staff dose and improves image quality
Radiographic images	Controllable	The number of image is proportional to patient dose
Fluoroscopy time	Partially controllable	Fluoroscopy time is proportional to dose
Magnification	Controllable	Radiation dose in increasing by magnification
Dose mode	Controllable	Low dose mode setting requires low tube current and less patient dose
Image geometry	Controllable	Increasing the source-skin distance (SSD) and decreasing patient detector distance reduces patient doses

Table 5. Operator related factors affecting patient radiation doses.

there is a known, relevant, and acceptable reason for this deviation. Practitioners and referrers should understand the following hits about DRLs for best practices [14]:

1. DRLs are not dose limits; they should be used as investigation levels;
2. DRLs are not applicable to individual patients;
3. comparison with DRLs shall be made using mean/median values of a sample of patient doses;
4. the use of DRLs should be made in conjunction with the evaluation of the required image quality or diagnostic information;

5. DRLs should be applied with flexibility, allowing tolerances for patient size, condition, etc.;
6. values that are UNDER the DRLs may not necessarily be optimized values;
7. values that are OVER the DRLs should require an investigation and optimization of the X-ray system or operational protocols;
8. the goal in using DRLs is not to reduce patient doses if image quality or diagnostic information is compromised; and
9. compliance or faults with DRLs should be discussed with the staff of the imaging department.

9. Conclusions

Image-guided intervention is safe and effective technique of choice to replace invasive intervention such as surgery. The frequency of interventional procedures is increasing and expected to increase in the future. Advances in imaging modalities will lead to introduction of a new complex interventional procedure. The risks of radiation-induced skin injuries (erythema) are expected in all complex procedures. Training of staff in fluoroscopic techniques will prevent patients from avoidable radiation risks and skin injuries.

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