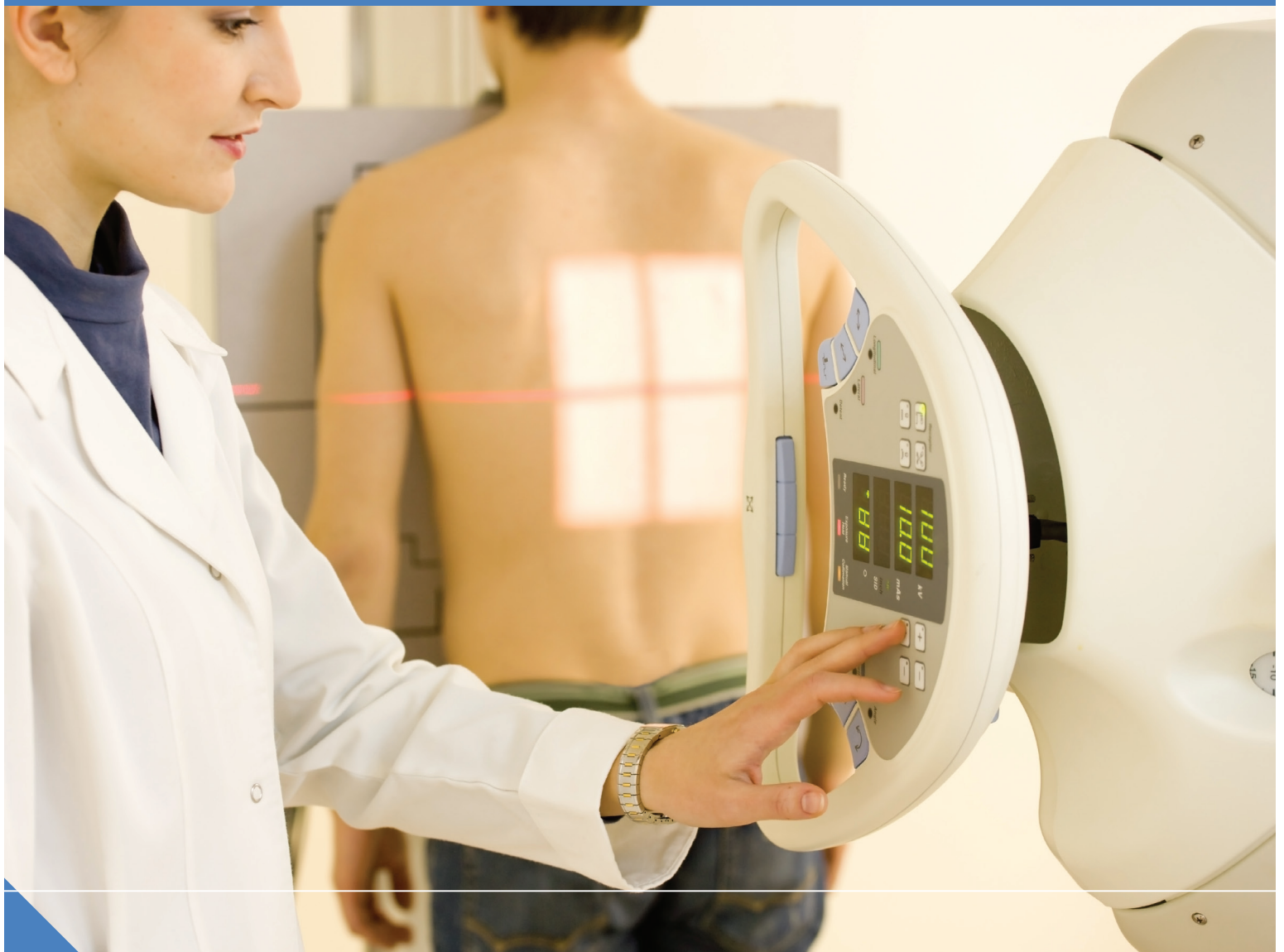


# MEDICAL IMAGING PRIMER

WITH A FOCUS ON X-RAY USAGE AND SAFETY



Canadian Association of Radiologists  
L'Association canadienne des radiologistes

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## WITH A FOCUS ON X-RAY USAGE AND SAFETY

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# INTRODUCTION

## PREFACE

The aim of this primer is to provide a concentrated and focused information package as a quick reference guide for students, pertaining to diagnostic radiation usage and safety, with a focus on modalities that involve the use of x-rays. Medical schools throughout the world emphasize radiological examination interpretation, but through our combined experience, we have concluded that little is taught on the science behind these examinations and the potential harm of exposure to radiation of certain energy. This primer gives a brief overview of ionizing radiation, the dosage associated with various radiological examinations, the precautions that need to be taken with a pregnant patient and the techniques of basic protection from radiation exposure as a physician, student or resident. We hope that through this primer, an important gap of knowledge will be filled that will ultimately result in better decisions, with safer patient outcomes.

## OBJECTIVES & AIMS

- To know how x-rays are formed and the various sources of ionizing radiation
- To know the biological effects of ionizing radiation
- To know how to protect oneself when working in areas that have sources of ionizing radiation
- To know the management options for pregnant patients requiring medical imaging
- To know the management options for a patient who has had a medical x-ray examination and was subsequently found to be pregnant
- To recognize unresolved clinical and scientific questions related to medical imaging
- To communicate with patients and their families about the risks and benefits of medical imaging

# I. ABOUT RADIATION

Humans are constantly being exposed to natural sources of radiation, including rays that reach us from outer space and rays from the sun. In addition, some foods that we ingest contain naturally-occurring radioactive isotopes, such as potassium and carbon. The environment that we live in may also contribute to our exposure to radiation, such as of inhaled radon gas. Not only are we exposed to natural sources of radiation, but manmade sources, including medical equipment, also contribute to our radiation dose.

The radiation that we are exposed to can be ionizing or non-ionizing, depending on whether or not the radiation has enough energy to remove an electron from an atom with which it interacts. Ionizing radiation, by definition, is any type of subatomic particle or high-energy photon that causes the formation of ions (electrically-charged atoms or molecules) when interacting with matter. These ions can lead to biologic damage in cells. Cosmic rays, neutrons, alpha particles, x-rays, ultraviolet rays of certain wavelength, and gamma rays are all forms of ionizing radiation. They contain enough energy per

photon to eject electrons from the atoms with which they interact. Visible light, infrared waves, most wavelengths of ultraviolet rays and radiofrequency waves, on the other hand, are non-ionizing.

In order to image the body, various imaging modalities are available. Most of these require the use of radiation to obtain a clear depiction of the area being investigated. X-rays, gamma rays and radiofrequency waves are all forms of electromagnetic radiation that are commonly used in imaging departments. These forms of radiation, and a collection of others (such as cosmic rays, ultra violet rays, visible light, and infrared rays), all make up what is known as the electromagnetic spectrum. Each of these types of electromagnetic radiation carries a certain amount of energy with it. The higher the frequency of the wave, the larger its associated energy. Thus, infrared, radiofrequency, and visible light have less energy than x-rays, gamma rays and cosmic rays. Table 1 shows examples of ionizing and non-ionizing sources of radiation.

Type	Examples where used
Non-Ionizing Radiation	
Radio Waves	Radio Station
Microwaves	Radio Station
Infrared Waves	Remote Control
Visible Light	Light Bulb
Ultraviolet Waves	Bactericidal Lamps
Ionizing Radiation	
X-rays	Medical X-rays
Gamma Rays	PET Imaging

Table 1: Ionizing and non-ionizing sources of radiation.

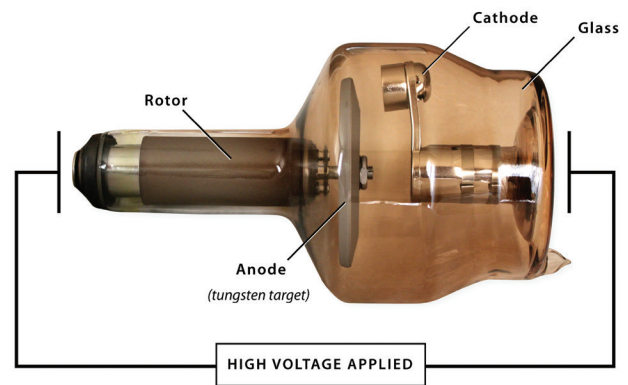
## 2. RADIATION IN MEDICAL IMAGING

Both ionizing and non-ionizing forms of radiation are used in diagnostic imaging departments. Imaging techniques that involve x-rays (such as plain film radiography, digital radiography, CT scans, mammography and fluoroscopy) all employ ionizing radiation. Nuclear medicine techniques (PET and SPECT imaging) also utilize ionizing radiation, in the form of gamma rays. MRI uses non-ionizing radiation (radiofrequency waves). Ultrasound uses pressure waves (mechanical waves) to image the body. Note that these sound waves are only mentioned here for the sake of presenting most of the modalities encountered in an imaging department. They are not classified as electromagnetic radiation.

In all imaging techniques (excluding ultrasound, MRI and nuclear medicine) an external source generates photons in the form of x-rays that become incident on the body. These x-rays are then absorbed or scattered (change trajectory and diverge from the beam path) as a result of interactions within the body. The beam that emerges after passing through the patient is thus attenuated, or less intense (it has lost some of its photons as it passed through the area being imaged, as they were removed through scattering or absorption). This attenuated beam then reaches a detector and allows for the generation of images.

In nuclear medicine, on the other hand, the radioactive source is not external, but internal. The patient is administered a radionuclide, typically through injection or inhalation. Initially, the radionuclide (or source) is bound to a molecule that will be metabolized by the body part or pathological tissue being investigated (the target). The radionuclide is unstable and is constantly undergoing radioactive decay, releasing gamma radiation (gamma rays,  $\gamma$ -rays). As this radionuclide pools in the target, gamma emission from the target will intensify. An external detector measures gamma radiation, which is used to produce the medical images.

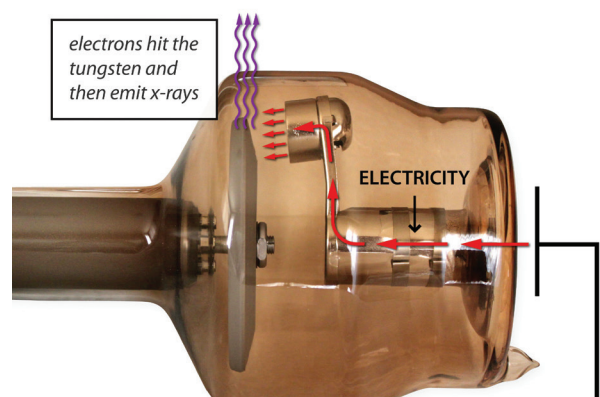
X-rays and  $\gamma$ -rays are defined by their origin in the nucleus. X-rays originate from outside the nucleus, while gamma rays originate from inside the nucleus of a radioactive atom. The production of an x-ray beam in a clinical imaging system is performed by the x-ray tube.



**Fig. 1a-** A diagram of an x-ray tube. The glass that seals the inside of the tube produces a high vacuum. A large voltage is applied between the cathode and the anode (typically made of tungsten).

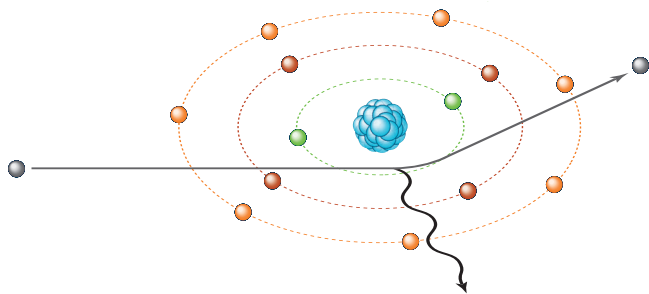
Inside the x-ray tube, an electron beam is generated by liberating electrons from the filament via thermionic emission (heating of the filament). Electrons within the beam are accelerated towards the anode (usually made of tungsten, molybdenum or rhodium) via tube potential or the tube anode. Once these electrons reach the target, the result of the interaction is a transfer of the electron's kinetic energy (through the acceleration inside the tube caused by the tube potential, or kVp) into heat and x-ray photons (1).

The continuous x-ray spectrum that is produced by a beam of electrons is referred to as bremsstrahlung (braking) radiation.



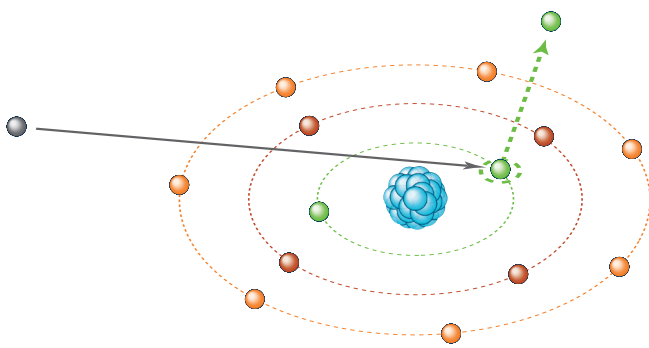
**Fig. 1b-** Production of continuous x-rays from an x-ray tube. Heating of a filament liberates electrons that are then accelerated towards the anode. The abrupt stopping of electrons results in the production of x-rays.



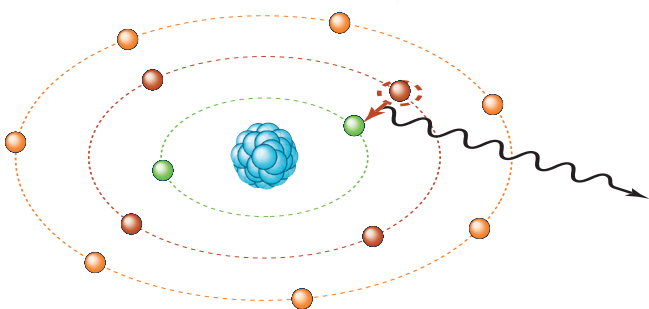


**Fig. 2-** Generation of bremsstrahlung or "braking radiation". When the incident beam of electrons is in the vicinity of the nucleus, it can experience a sharp deflection that results in energy loss by the emission of photons.

If a sufficient tube voltage is applied, the incident electrons may eject electrons from the target atom. Electrons from higher shells then fill the produced vacancy, resulting in the emission of characteristic x-rays.



**Fig. 3a-** When the incident beam of electrons has sufficient energy, it can eject electrons from the target (green arrow).



**Fig. 3b-** The produced vacancy is then filled by electrons from higher shells (orange arrow), resulting in the emission of characteristic x-rays.

The origin of  $\gamma$ -rays is the nucleus of a radioactive atom. When the nucleus is radioactive, it is unstable and must undergo a radioactive transformation to reach a stable state. Radioactive transformations consist of beta- decay,

beta+ decay, electron capture and alpha decay. A full description of the transformations is beyond the scope of this primer and interested readers are encouraged to read any nuclear medicine textbook (2).

When  $\gamma$ -rays are used in imaging, radiation is present after the medical procedure. This is because  $\gamma$ -rays are produced through a radioactive transformation, thus the source is constantly emitting radiation. The intensity of radiation emitted by the source is governed by the half-life. As a result, the patient remains radioactive until the entire injected source has either passed from the body (excrement, urination and sweat) or enough time has elapsed such that the source has decayed to natural background radiation levels. A patient exposed to x-rays, on the other hand, is not radioactive after the examination because x-ray production is terminated by the x-ray tube.

In diagnostic x-ray imaging, images are formed by the interaction of the x-ray beam, the patient and the detector. As the x-ray beam passes through the patient, the photons interact with the tissues of the body and are absorbed by the patient. The degree of absorption is related to the density of the material that is in the beam's path. Dense objects (such as bone and metal) have a high degree of photon absorption, while less dense objects (such as fat and water) absorb less photons. The differential absorption of photons by different materials in the photons' path results in the beam exiting the patient with different intensities. This is known as the transmittance beam. A detector is used to measure the intensity variation, thus providing information on the different densities in the beam's path.

In radiography, the transmittance beam is visualized using plain-film detector or with digital detectors. In plain-film radiography, areas of high intensity (thus low material absorption) within the transmittance beam result in blackening of the film, while areas of low intensity (thus high material absorption) will result in less blackening of the film. The film will remain white in areas with no photons.

Since the human body is made up of tissues with varying densities, the film that results when x-rays are used to image the body is in grayscale, where black corresponds to tissues with little attenuation (such as air) and white corresponds to tissues with a high degree of attenuation (such as bone).

The simple x-ray can be done in different orientations in order to view different aspects of the patient's anatomy. The orientations most frequently used are the PA (posteroanterior, or back-to-front), AP (anteroposterior, or front-to-back) and lateral (side view). Note that instead of using photographic film, digital radiographs can be produced. Image formation using digital detectors are beyond the scope of this primer and readers interested in this topic are referred to (1). Typical tube voltages range from 50-150 kVp.

Mammography is used to identify any calcification (seen in some types of breast cancers), as well as any areas of hypodensity or hyperdensity that can be seen in other cancers (1; 4). It is employed both as a screening tool and for diagnosis. Mammography also uses x-rays to visualize the breast and detect any abnormalities in this organ; however, there are fundamental differences between a mammography system and a diagnostic x-ray system. Due to the tissue characteristics of the breast and of pathology of interest, mammography systems utilize a lower tube potential than diagnostic x-ray systems (15-35 kVp vs. 50-150 kVp). In addition, two compression plates are used to decrease breast thickness and minimize motion, thus resulting in less scatter radiation and better overall image quality.

Fluoroscopy is a real time x-ray examination, which utilizes a series of low-dose x-rays obtained over time. It is useful for the assessment of the gastrointestinal tract, the urinary tract, and the musculoskeletal system. Angiography is a specialized fluoroscopic examination in which a contrast agent is used to highlight vasculature in the patient. Contrast is a radiopaque (high density) material injected into the blood vessels of the patient. Vessels containing contrast show up dark on the image, while areas without contrast show up bright. Advanced techniques, such as Digital Subtraction Angiography and Road-mapping can be utilized to improve vessel visualization and also guide percutaneous tools.

Computed tomography scans (or CT scan), in the simplest sense, utilize thousands of x-rays of the patient, taken at various angles around the patient. The most common CT systems employ an x-ray tube and detector, which simultaneously revolve around a 'slice' of the patient, while taking x-rays. Through image processing, each

acquisition is used to reconstruct the slice of the patient imaged. This process is then repeated for different areas of the patient, thus resulting in a 2D stack of axial images of the patient. Advanced data acquisition techniques and computer processing can be employed to produce a variety of images, including 3D perspectives. CT scanners that are in use today have more than a single row of detector arrays (multi-detector CT, MDCT). Thus, they can simultaneously collect more than a single slice. 16-slice and 64-slice MDCT scanners are commonly encountered in imaging departments and some institutions have 320-slice scanners (3). In addition to this simultaneous technique, helical CT imaging allows for the continuous movement of the CT table during imaging. If multi-slice imaging is done in conjunction with helical scanning, reductions in scan time are possible.

In Positron Emission Tomography (PET), the radioactive decay of the administered source (such as Fluorine-18) results in the emission of positrons (electrons that are positively charged). This particle then annihilates with a nearby electron and two gamma rays are emitted that are 180 degrees apart. Thus, PET uses a ring of detectors that surround the patient to register the emitted photons. Once photon pairs have been detected, computers can reconstruct an image of the distribution of the radioactive source. Since the source is internal, different tissue compartments and the locations of differing tracer (i.e. a pharmaceutical labeled with a radioisotope) uptake are shown by areas of hyperdensity (hot spots, high uptake of the tracer) or hypodensity (cold spot, low uptake of the tracer) (1; 4).

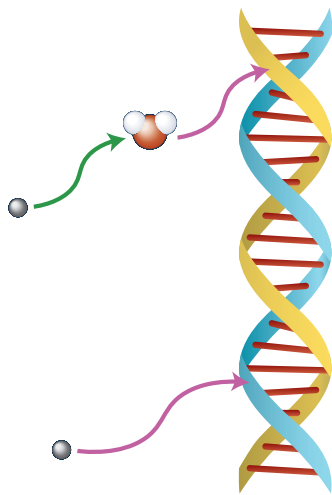
Single photon emission tomography (SPECT) is another nuclear medicine procedure that is similar to PET imaging. It also requires the injection of a radioactive isotope (such as Technetium-99m) that is usually attached to a pharmaceutical. However, unlike PET imaging, the radioisotope used in SPECT imaging emits a single  $\gamma$ -ray when it decays. Gamma cameras capture the emitted gamma rays and reconstruction of the resulting image can be done using different techniques, such as filtered back-projection. SPECT has many clinical applications, including cerebral blood flow imaging and myocardial imaging.



### 3. IONIZING RADIATION: BASIC CONCEPTS

#### 3.1 ACTION OF IONIZING RADIATION

Recall that gamma rays (used in nuclear medicine) and x-rays (used in CT, radiography, fluoroscopy and mammography) are both classified as ionizing radiation (see Section 1). When ionizing radiation interacts with matter, it deposits some or all of its energy into the material, resulting in excitations, ionizations and heating of the exposed area. Specifically speaking, the interaction of radiation results in the ejection of an electron from the target atom. If this electron then interacts with critical targets in the cell, such as DNA, and produces ionizations, the radiation is said to have a direct action. Alternatively, the ejected electron can interact with other molecules in the cell (such as water, H<sub>2</sub>O) and produce free radicals (OH) that then travel to and interact with the critical target; a process referred to as the indirect action of radiation. Fig. 4 shows the two possible actions of radiation.



**Fig. 4-** Action of ionizing radiation. When the radiation ejects an electron (grey in the figure), the electron may interact with water molecules and produce free radicals (top part of the figure). These radicals can then become incident onto the critical target. This action is referred to as the indirect action of radiation. In the direct action (bottom part of the figure), the radiation ejects an electron that then interacts with the critical target and produces biological damage.

The action of radiation, whether direct or indirect, results in the diffusion of either free radicals or electrons, which may then become incident on the DNA in the cell and damage it by altering its structure in numerous ways.

Hydrogen bond disruptions, as well as single or double strand breaks, may result (1). Once these chemical changes are induced, the cell might respond by activating repair mechanisms and restoring the damage. However, if repair errors occur, the cell might be eliminated through apoptosis (programmed cell death) or mitotic death (death during the next cell division cycle). If the repair errors occur and the cell does not get removed, then a mutated cell results.

When it comes to describing an organ system, if error-free repair of cells takes place following radiation exposure, then no observable effects will be seen. No effects will also be observed if the unstable cells are eliminated, provided that not many cells are killed. If a large dose is given and too many cells are killed, the organ might lose some of its function. However, such high-focused doses are not typical of medical imaging. Finally, if the mutated cells continue to survive, this may result in the formation of cancers or hereditary effects if the mutations occur in somatic or germ cells, respectively (5). An organ's response to radiation and its consequent ability to repair the damage can depend on a number of factors, including the received dose, the rate at which the dose was received, the presence of certain molecules after exposure to radiation, the type of radiation used, the age of the exposed individual and the location of the damage within DNA molecules.

#### 3.2 REGULATORY AGENCIES AND RADIATION EFFECTS

Numerous advisory committees have been established to review current scientific findings and print reports to assess the effects of ionizing radiation. These include the International Commission on Radiological Protection (ICRP), the National Council on Radiation Protection and measurement (NCRP) and the committee on the Biological Effects of Ionizing Radiation (BEIR). The recommendations of the ICRP form the basis for radiological protection in Canada and most countries (6).

The ICRP classifies the biological effects of ionizing radiation into two categories: deterministic and stochastic (7). Deterministic effects are those whose severity increases with dose and they occur above a certain threshold. Examples of these effects are cataracts and erythema (skin reddening). Stochastic effects are

those whose probability of occurrence increases with dose. Radiation-induced cancers and genetic effects fall in the stochastic category. The current consensus among advisory committees is that stochastic effects follow a linear, non-threshold model (7; 8), which implies that any dose of radiation, regardless of how small it may be, is believed to carry an associated risk. It should be noted here that the use of the linear non-threshold model in cancer risk estimates stems from extrapolation of risks from high dose and high dose rate exposures, where most of the data comes from the atomic bomb survivors. However, there is an ongoing debate regarding the true effect of ionizing radiation at low doses, such as those used in imaging procedures. Some researchers believe in the existence of adaptive repair mechanisms based on radiobiology studies. Due to the limited scientific knowledge regarding low dose exposures, most agencies prescribe the ALARA principle (As Low as Reasonably Achievable), simply put – since we don’t know the extent of damage caused by low levels of radiation, we should mitigate risk to future generations by using as low radiation doses as possible. The reader is directed to the following for further discussion of the effects of low doses of ionizing radiation (8; 9).

When a patient is being imaged using ionizing radiation, the health effects that are of most concern are the stochastic effects. Assuming a linear non-threshold model, any procedure that imparts a dose to the patient increases the risk of these effects. The deterministic effects, on the other hand, are observed with large doses that are not typical of the majority of the imaging procedures. Recommended dose limits have been set by the ICRP for radiation workers and for the public (see Section 4, Table 4). The ICRP does not put a limit on medical exposures of patients. It is left

up to the physician to decide if the benefits of a medical exam outweigh the risks from radiation, or whether to proceed with care without the diagnostic information. However, the ICRP emphasizes optimization of radiation protection measures for procedures using ionizing radiation (10).

### 3.3 IONIZING RADIATION: QUANTIFICATION, EXPOSURE AND RISK

A number of quantities are used to refer to the radiation dose. The term exposure describes the ions (i.e., charged particles) produced by a radiation field within a given volume of air. If two different materials are exposed to the same radiation field, the amount of energy that they absorb will not be the same. Although exposure describes the ionization present, it does not explain how the body will respond to that energy. The term absorbed dose, which is measured in Gy (where 1 Gy = 1 joule/ kg) is the amount of energy absorbed per unit mass. If the same body part is exposed to two different types of ionizing radiation, the biological damage produced will not be the same. In addition, the severity of the biological damage depends on the type of radiation. To reflect the biological effects of radiation, the term effective dose is used, which is measured in the unit referred to as the sievert (Sv). This is the best measurement when comparing the radiobiological effects of different types of medical procedures (11). Non-SI (International System of Units) units and terms such as the rad (radiation absorbed dose), the roentgen and the rem also exist; however, their use is now discouraged (11). Readers who need to use these units can find conversion factors and definitions readily available in any older medical physics textbook.

Radiation Source	Contribution to the Total Effective Dose (%)
Natural Background	50
Medical Radiation	48
Consumer Products	2
Other (Nuclear Power Plants/Fallout)	< 0.1

Table 2- The contribution of the common sources of radiation. Data from (13).

Procedure	Effective Radiation Dose (mSv)	Natural Background Radiation Equivalent
Bone Densitometry	0.01	1 day
Chest X-ray	0.1	10 days
Galactography	0.7	3 months
Mammography	0.7	3 months
IVP	1.6	6 months
X-ray (Upper GIT)	2	8 months
X-ray (Lower GIT)	4	16 months
Myelography	4	16 months
<b>CT scans</b>		
Sinus	0.6	2 months
Cardiac CT for Calcium	2	8 months
Head	2	8 months
Colonography	5	20 months
Chest	8	3 years
Abdomen	10	3 years
Body	10	3 years
Spine	10	3 years

**Table 3-** Radiation dose for various procedures compared to background radiation. Data from (14;15).

To put the doses received from medical procedures into perspective, a reference to natural background radiation is helpful. In everyday life, humans are exposed to a certain level of background radiation from natural sources such as cosmic rays, atmospheric gas (radon) and the decay of radioisotopes of carbon and potassium present in the body (see Section 1). The annual effective background radiation dose in Canada is 1.77mSv (12). The natural background dose around the world varies between 1-10mSv, with an average effective annual dose of 2.4mSv (8). Besides natural background, the population is exposed to other sources of radiation. Table 2 gives a depiction of the sources to which humans are commonly exposed. When radiological procedures are carried out, certain doses are received, depending on the type of exam and the

area being imaged. The radiation dose that is received from various imaging procedures is shown in Table 3, along with a comparison to the background radiation that one would be exposed to from everyday living.

Recommended dose limits have been set by the ICRP for radiation workers and for the public (see Section 4, Table 4). The ICRP does not put limits on the dose received by the patient. Justification of a medical procedure that involves the use of ionizing radiation is left to the physician, who should weigh the benefits of the procedure against the risks. In addition, the ALARA principle must be adhered to, where proper measures are taken to avoid unnecessary exposures.

## 4. IONIZING RADIATION: PROPER PROTECTION

For the purpose of radiation protection, recommended dose limits have been established by the ICRP for radiation workers (individuals exposed to man-made radiation due to their occupation) and for the remainder of the population. These dose limits are shown in Table 4. Note that these limits do not include doses obtained from medical procedures or background radiation.

As all radiological imaging that uses ionizing radiation is currently assumed to be associated with some level of risk, the protection of both the patient and staff needs to be ensured. There are no current specific limits on the levels of exposure from medical imaging. Accordingly,

an assessment of the benefit of each exposure for the patient must be weighed against the perceived risks. In order to achieve the maximum benefit for the patient, any possible reduction in the total risk of the procedure must be actively pursued. However, a reduction in the risks of a procedure may not necessarily equate to a reduction in the radiation dose to be received by the patient. For example, image clarity may be compromised in order to reduce the overall dose of radiation to the patient. However, in some cases, reduction in image clarity would be of a greater risk (in misdiagnosis) to the patient than the potential risk of radiation exposure.

Type of Limit	Occupational Exposure	Public
Whole Body	20 mSv/year averaged over periods of 5 years	1 mSv/year
Annual Dose in:		
Lens of the Eye	150 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and Feet	500 mSv	-

**Table 4-** Dose limits recommended by the ICRP for planned exposure situations (7).

There are three principles of radiation safety to reduce occupational exposure and they are: time, distance and personal protective equipment (PPE). Time refers to the amount of time spent in the vicinity of radiation. Reducing the time in a procedure room while x-rays are on, or around nuclear medicine patients, will reduce occupational dose. Distance refers to the spatial separation between staff and radiation. Exposure reduction typically follows the inverse square law, where exposure is reduced by  $1/(\text{distance})^2$ . For instance, increasing one's distance from 1 meter to 3 meters from a radiation source would reduce the dose by 1/9th of the original dose. Spatial separation is achieved via designated "safe" areas. Medical personnel normally should not be permitted in the investigation room, unless it is completely necessary. In such cases, the three principles of radiation safety should be followed. Limitations of the numbers of staff present to the minimal number required at any investigation will also lead to a lesser margin for human error and exposure (16). Safe areas are rooms that allow medical personnel to view the procedure being performed without exposure to the radiation source. These rooms are usually adjacent to the procedure room and have a window in the adjoining wall for visualization. In areas where portable x-ray devices are used, such as in the emergency department, ICU or operating rooms, spatial separation can also be achieved using portable boundaries or screens. In these areas, only personnel essential for the examination should be present in the vicinity (17). PPE refers to the proper use of protective equipment. These include: lead aprons, vests, skirts, thyroid collars, lead-lined glasses, overhead shields, table skirts and portable lead barriers. When available, it is strongly recommended that staff utilize PPE to reduce their occupational exposure. In addition to the three safety principles, a qualified expert, such as a medical physicist, must evaluate procedure room shielding, to ensure the staff and public around the room (or in the control console) are sufficiently shielded from medical radiation.

A final accessory to barrier protection is the use of radioactive dosimeters to measure the level of radiation that is absorbed by any individual medical personnel member. For those who are considered to be at high risk of occupational exposure, use of a dosimeter is essential and is mandatory in all Canadian provinces, based on provincial occupational safety laws. Dosimeters can be worn in two places. First, they are worn underneath the other protective garments in order to measure the level of radiation that still penetrates the body through the barriers, and can be used to assess whether the equipment is being used in the most effective manner. A second dosimeter can also be worn over the lead apron, usually hanging near the neck, in order to take a measure of the level of radiation absorbed by the face, neck, skull and eyes. Dosimeters will provide a review limit for the individual medical personnel to ensure that safe working levels have been achieved and that their monthly, quarterly and yearly levels are satisfactory (18).

## 5. IONIZING RADIATION: THE PREGNANT PATIENT

Currently, in the general public, as well as in the medical field, there is speculation about the risk of radiological investigation to an expectant mother and her unborn child. A literature review will bring up a large amount of conflicting data that is used to both support and detract from the use of imaging in pregnancy (19). The effect of radiation in-utero depends on the dose that is received and the gestational stage during which the conceptus receives the dose. The gestational period can be divided into three stages: pre-implantation, organogenesis and fetal development. Radiation injury in the first stage is believed to result in an “all or nothing” effect, where either prenatal death occurs, or typically normal development proceeds. The threshold is believed to be at least 60 mGy and this threshold varies greatly. It should be noted that the background rate of miscarriages (spontaneous abortions) is between 30-50% at this stage (1). In the organogenesis stage, the differentiation of cells into

various organ systems takes place, and thus, congenital malformations may occur. Although uncommon, given diagnostic doses, for women exposed during the 1-8 week period, physical growth retardation of the fetus is the most common effect at this stage of development (20). Finally, in the fetal growth stage, nervous system abnormalities are the major concern due to radiation exposure. Defects in the central nervous system, which can lead to outcomes such as microcephaly, mental retardation and seizures, may be seen 8 to 15 weeks post implantation, the period of the greatest neuronal development in the fetus (20). However, a risk of mental retardation also exists in those women exposed in the 16-25 week period. It should be noted that radiation induced malformations are believed to occur above a certain dose threshold. Table 5 shows an estimation of the fetal doses that can induce various malformations and the gestational period during which the greatest risk exists (21).

Malformation	Time of Greatest Risk Post Conception (Weeks)	Estimation of Dose Threshold (mGy)
Microcephaly	8-15	≥ 20,000
Medical Radiation	8-15	60 – 310
	16-25	250- 280
Other (malformations of the skeleton, genitals, eyes)	3-11	≥ 200
Reduction of IQ	8-15	100

Table 5- Radiation-induced malformations from fetal exposures during various gestational stages. Data from (21).

For comparison with the values in Table 5, the doses that the fetus receives when the mother undergoes diagnostic examinations are shown in Table 6 (22).



Exam	Fetal Dose (mCy)
<b>Radiograph</b>	
Upper Extremity	< 0.01
Lower Extremity	< 0.01
Chest (2 Views)	< 0.10
Cholecystography	0.05–0.60
Pelvis	0.40–2.38
Upper GI Series (Barium)	0.48–3.60
Hip and Femur Series	0.51–3.70
Abdomen (kidneys, ureter and bladder)	2.00–2.45
Lumbar Spine	3.46–6.20
Urography (intravenous pyelography)	3.58–13.98
Barium Enema	7.00–39.86
Retropylorography	8
<b>CT scans</b>	
Head	< 0.50
Chest	1.00–4.50
Abdomen (10 slices)	2.40–26.0
Abdomen and pelvis	6.40
Pelvis	7.30
Lumbar Spine	35.00
<b>Other</b>	
Ventilation-Perfusion Scan	0.60–10.00

**Table 6-** Estimates of fetal radiation doses from common diagnostic procedures. Data from (22).

In most radiological examinations, the dose that is received by the developing fetus is less than 50 mGy (see Table 6). It should be noted that the values in Table 6 are approximations and may vary with the scanning parameters used, as well as the variations in the female anatomy. In most imaging procedures, the fetus receives smaller doses than the mother because of the protection in the mother's uterus (23). In all radiographic imaging of pregnant women, there is an element of radiation dosage to the fetus through both direct exposure and indirect exposure. Direct exposure occurs when the fetus is within the field that is imaged. This includes investigations such as pelvic and abdominal imaging. Indirect exposure is due to the internal transfer of radiation from maternal tissues to the fetus. Investigations such as exams of the mother's head, neck, extremities and chest carry very little direct exposure risk with the correct protective measures, yet will still carry some degree of indirect exposure. Indirect exposure is of greater concern in investigations where there is a likelihood of placental transfer, such as those examinations that use radioactive iodine and gallium (20).

Both the public and the physicians' perception of the risks of x-ray imaging influence the current trend of using these investigative techniques on pregnant women. In a study of 98 women, the perceived teratogenic risk has been reported to be much higher in those who have undergone radiodiagnostic procedures (25.5%) than those who have not (15.7%) (24). This is reflective of the general perception of radiological imaging as being harmful to the fetus. Studies conducted on physicians' perception of teratogenicity due to radiological investigations have shown that physicians

usually overestimate the risk of harm and, therefore, are cautious about the use of x-ray on pregnant patients. In a Canadian study, obstetricians and family physicians were asked about the risks to the fetus when the mother undergoes an abdominal radiographic or CT examination. In a survey of 287 family physicians and obstetricians, 44% of family physicians and 11% of obstetricians estimated the teratogenic risk of an abdominal radiograph to be >5% (25). In addition, 1% of family physicians said they would recommend an abortion if a mother is exposed to radiation from an abdominal radiograph, while 6% recommended abortion following an abdominal CT exam (25). These examples illustrate that even those ordering the investigations carry many misconceptions about the implied risks for pregnant women. This over-caution may originate from a lack of knowledge of the radiation doses from the different imaging modalities (26), or due to an overestimation of the inherent teratogenic risk.

Despite the current public perception, most radiographic imaging techniques result in low fetal exposures, below 50mGy, where significant increases in risk to the fetus have not been observed. As in all medicine, the risks and benefits of each diagnostic procedure should be assessed on a case-by-case basis. In addition, an understanding of the doses involved in radiological investigations should be sought after, so that increased anxiety levels for pregnant patients and unnecessary terminations can be avoided.

**The American Congress of Obstetricians and Gynecologists (ACOG) states that fetal risk is minimal with doses under 50 mGy, and that doses over 100 mGy may result in malformation of 1% above incidence.**

## 6. ALTERNATIVE NON-RADIATION IMAGING MODALITIES

In order to avoid any of the risks of ionizing radiation, which vary depending on the received dose, alternative imaging modalities can be utilized. Ultrasound and magnetic resonance imaging (MRI) do not involve ionizing radiation and can be the modalities of choice in many situations.

### 6.1 ULTRASOUND IMAGING

Ultrasound imaging, which is sometimes referred to as ultrasound scanning or sonography, uses sound waves to produce an image of the body part being examined. In ultrasound imaging, a transducer is used to send high-frequency sound waves through the body. Ultrasound has application in many different medical fields, and can be used for both diagnostic and therapeutic procedures, such as biopsies or fine needle aspiration. Common applications of ultrasound include (27):

- Cardiology (echocardiography, which requires the use of a transesophageal probe)
- Gynecology and obstetrics
- Urology – in both external/internal imaging techniques for men and women, as well as using focused ultrasound to break up kidney stones by lithotripsy
- Musculoskeletal
- Intravascular ultrasound

Ultrasound imaging has many applications in medicine and is considered to be safe, with no reports of adverse clinical or biological effects due to exposure to ultrasonic radiation from millions of investigations since its initial inception and use (28). However, although ultrasound imaging can be used to investigate many pathological conditions, it does not work well in areas where there is a high amount of air, due to the inability for ultrasound waves to penetrate and transmit through air. Thus, it is not the best choice for the bowel and the stomach or areas obstructed by these organs, as well as the internal areas of bone and large joints (27).

### 6.2 MAGNETIC RESONANCE IMAGING

Magnetic resonance imaging (MRI) uses the properties of magnetism and resonance to generate an image of the area being investigated. In most clinical MR imaging, the hydrogen nucleus (a single proton) is used for imaging because of its abundance in the body. Other nuclei, such as phosphorus, sodium and carbon, can also be investigated to provide further insight into the metabolism of certain molecules (for instance ATP can be studied in phosphorus imaging). It should be noted that imaging of nuclei other than hydrogen is mostly done for research purposes and that clinical images are almost always done on hydrogen nuclei.

MRI is a valuable resource in investigating a broad range of conditions and can produce highly detailed images of soft tissues from multiple angles, allowing imaging of focal lesions and the detection of abnormalities that would otherwise be obscured on a single plane view (29). It has also been used to understand brain connectivity through a process called functional MRI (fMRI). When a brain area is active, blood flow increases to that area. However, the amount of oxygen extracted is less than that delivered, resulting in a decrease in the amount of deoxyhemoglobin present in the area, relative to the resting state. The MR signal used in fMRI is sensitive to the ratio of oxyhemoglobin to deoxyhemoglobin. Thus, the change that accompanies brain activation can be picked up on certain MR images and can be used to understand which parts of the brain are associated with which tasks.

### 6.3 OTHER OPTIONS

Outside of diagnostic imaging techniques, the invasive visualization of the site of interest is another option. Depending on the anatomy of interest, this can be performed telescopically (such as in a laparoscopy, endoscopy or arthroscopy) or through an open technique (30). Although telescopic techniques do not use ionizing radiation, these procedures require surgical expertise and carry with them the general risks of surgery, such as wound, infection, blood loss, perforation of visceral organs and reactions to the anesthetic agent (31). There may also be limitations to the area of anatomy that can be visualized in the procedure, such as the retroperitoneal organs and posterior aspect of the liver (31).

## 7. IONIZING RADIATION (X-RAYS, $\gamma$ -RAYS) AND THE LEARNER – IMPORTANT FACTS

- The handling of isotopes and the optimization of x-ray equipment is legislated and can only be performed by licensed personnel.
- Fluoroscopic equipment is used by non-radiologist physicians in the operating room, intensive care units, cardiac catheterization labs and in urological suites. The operation of this equipment will be by physicians trained in the equipment's use.
- If assisting in procedures using x-ray guidance, the following safety rules need to be followed:

1. Use of protective gear, which includes a lead apron to cover the chest, abdomen, pelvis and femurs. Protective eye-glasses and a lead thyroid collar should also be worn.
2. Keep hands and arms away from the x-ray beam.
3. Stand as far away as possible from the x-ray source during actual exposure.
4. Never turn your unprotected back to the active x-ray source.
5. If pregnant - avoidance.
6. Use protective x-ray barriers.
7. CT Scans can be observed safely from the technologist's console room. Precautions related to patients who have injected, ingested or inhaled isotopes will be clearly specified. Follow these precautions!

## 8. GENERAL INFORMATION ABOUT RADIATION DOSE AND THE EQUIPMENT

- Radiation dose is highest closer to the radiation source.
- The radiation dose decreases significantly with distance.
- Radiation barriers significantly decrease radiation dose.
- Scatter radiation can occur, especially during bone procedures.
- Guidelines for actual use of x-ray equipment is out of scope for this primer.
- The student can also be exposed to x-ray radiation on the wards when portable x-rays are being performed. In this case, observe the x-ray radiation signs and stay away from the x-ray source and the patient being examined.
- During radiology electives, the student may be exposed to x-ray procedures. If in the angiography suite or fluoroscopy units, use the same precautions as outlined in section 7.

## 9. X-RAY PROTECTIVE MEASURES IMPLEMENTED BY THE RADIOLOGY DEPARTMENT

There are many x-ray protective measures in place in the Radiology department to protect the patients, as well as the healthcare workers. These include:

- Lead lining of the x-ray rooms and doors, including general x-ray, fluoroscopy, angiography and CT. MRI and ultrasound rooms do not require lead walls.
- The doors to the x-ray rooms are closed prior to start of procedure.
- Any viewing windows from the control room into the imaging room are lead glass.
- Protecting lead or lead glass screens should be available in the imaging rooms to protect any personnel who must stay in the room to attend to the patient.
- X-ray areas should be clearly marked and limited to authorized personnel.
- Lead aprons, protective gowns and lead gloves and the thyroid collars must be readily available for protection also. All PPE must undergo quality assurance in accordance with the hospital's regulations or Health Canada Safety Code 35 to ensure PPE integrity.

# 10. EVIDENCE-BASED APPROACH TO ORDERING X-RAYS

The evidence-based approach in healthcare is a dynamic method of clinical decision-making, based on current and accurate evidence gathered through research in the management of any patient. Data gathered is explicitly utilized in Evidence-Based decision-making (32) and involves the systematic application of the best current and available evidence to evaluate a patient’s options for further management/treatment. Evidence-Based Healthcare (EBHC) can be applied to any step of the decision-making process in a clinical setting, including radiology. In Evidence-Based Radiology (EBR), the ever-expanding sea of medical knowledge and technology has made it a challenging task for radiologists to cater appropriate methods of investigations that are both clinically useful and cost-effective.

The increasing number and complexity of currently available radiological investigations provides radiologists with the task of applying gathered evidence. This knowledge must be applied to ascertain which would be the most sensible, cost-effective and valuable method of investigation for a particular case scenario. Applying the principles of evidence-based medicine; we can take a closer look at how to prioritize the different testing methods according to research evidence. As a general rule, radiation dosages should always be as minimal as possible. Therefore, radiological investigations carried out should only be requisitioned with the patient’s cumulative radiation history taken into consideration. To simplify and grade the radiation dosages, the Relative Radiation Level Designations from the American College of Radiologists (ACR) can be consulted in Table 7 (33).

Relative Radiation Level	Effective Dose Estimate Range (mSv)
None	0
Minimal	< 0.1
Low	0.1-1
Medium	1-10
High	10–100

*Table 7- relative radiation level designations form the ACR guidelines (33).*

Evidence-Based Radiology can be practiced in a multitude of clinical scenarios, each of which requires obtaining thorough patient history and performing a relevant physical examination.



## II. APPENDIX I: CASE SCENARIOS FOR EVIDENCE-BASED RADIOLOGY

### Case Study: Right Upper Quadrant (RUQ) Pain

Acute RUQ pain is a common clinical manifestation, which is associated with presentation of acute cholecystitis or choledocholithiasis. The most widely available methods of imaging for such cases are Real-Time Ultrasound, Cholescintigraphy (Nuclear Medicine), Plain X-Ray, and Computed Tomography. We shall now take a look at a clinical case scenario and discuss an evidence-based radiological approach to choose the most logical method of imaging in each situation.

### EBR Case Scenario I

**Problem: 42-year-old female presenting with acute Right Upper Quadrant pain.**

This case scenario has a high pre-test probability for gallbladder disease. What are the available radiological tools for visualizing the gallbladder? A review of the imaging options in this case reveals a series of investigation possibilities: Real-time ultrasonography, nuclear medicine (hepatobiliary) scan, plain x-ray, computed tomography (CT scan) (33). If we are to use the theory that the lowest dose of radiation is the best line of management, we can conclude that real-time ultrasonography would be the first-line approach to imaging the gallbladder region of this patient. The radiation dose that the patient experiences is zero. Also, according to the ACR Appropriateness Criteria, real-time ultrasonography is the standard first-line method for investigating gallbladder disease.

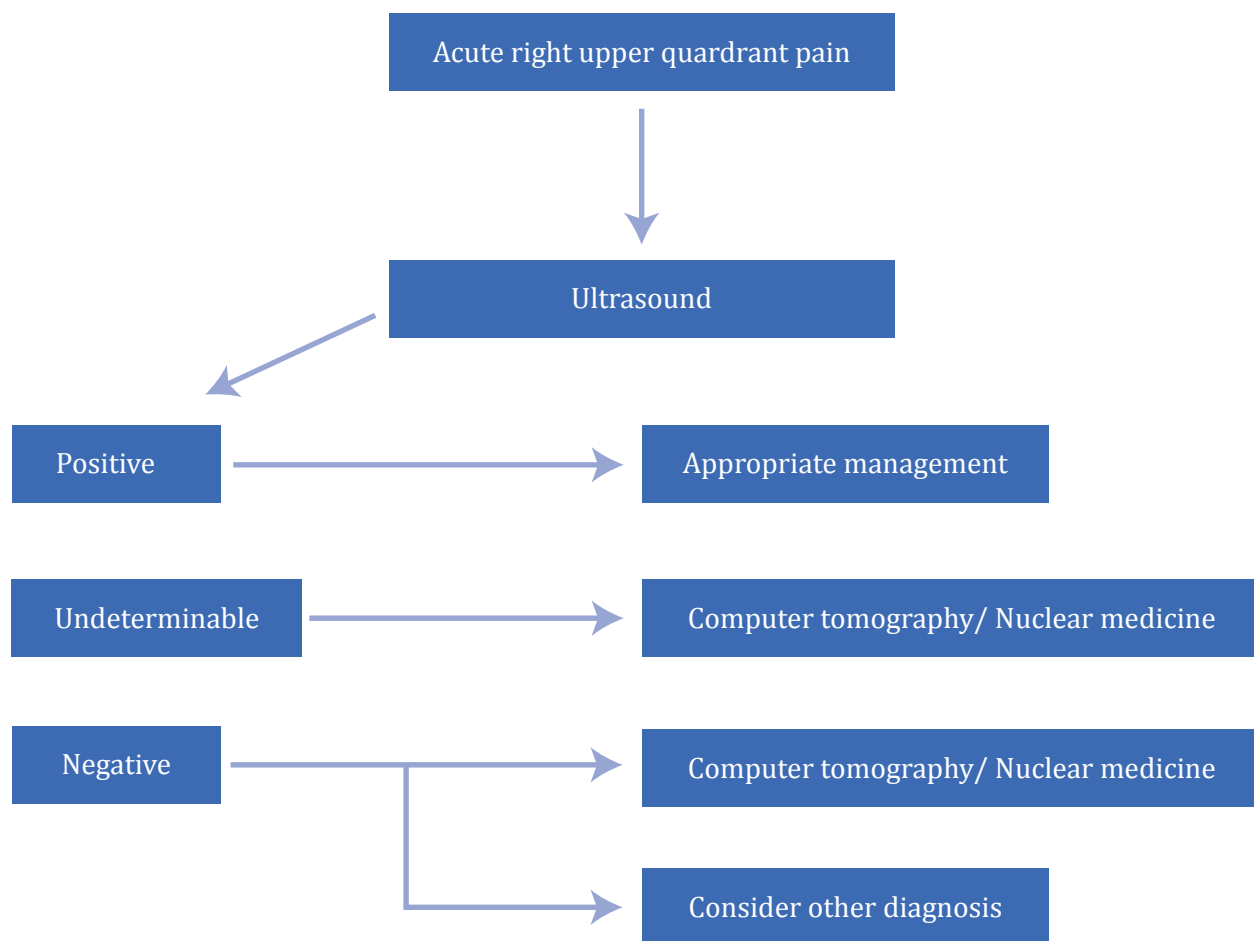
Real-time ultrasonography, as a diagnostic measure for cholelithiasis, is a painless and virtually risk-free procedure (34). Although a six-hour fast is required in preparation for the test, the test itself takes approximately 15 minutes to perform. Up to 95% of the patients are known to have adequate results that require no

further testing. The two major criteria for the diagnosis of gallstones are (1) non-visualization of the gallbladder and (2) echogenic densities that can cast an acoustic shadow. These criteria refer to a fibrotic gallbladder filled with small gallstones. RTUS has a sensitivity of 89% and a specificity of 97% (34). A simple flowchart of the basic approach to making a diagnosis of acute cholecystitis due to gallstone obstruction is outlined in Figure 5 (27).

Magnetic resonance imaging would not be indicated due to the relatively high cost of the procedure. There are, however, scenarios with right upper quadrant pain where other methods of radiological investigations must be employed. Some examples are:

- Looking for complications of gallbladder disease
  - Abscess formation
  - Perforation
  - Gallstone ileus
- Inability to visualize the gallbladder due to
  - Overlying gas
  - High position of the liver
  - Calcification within the gallbladder wall

In the above instances, the next most appropriate option would be either a nuclear medicine or CT scan. Although each of these techniques exposes the patient to radiation doses, in each exam the limitations of ultrasonography are overcome and it is possible to visualize the area of concern with a higher clarity.



**Figure 5-** Diagnosing acute cholecystitis (27).

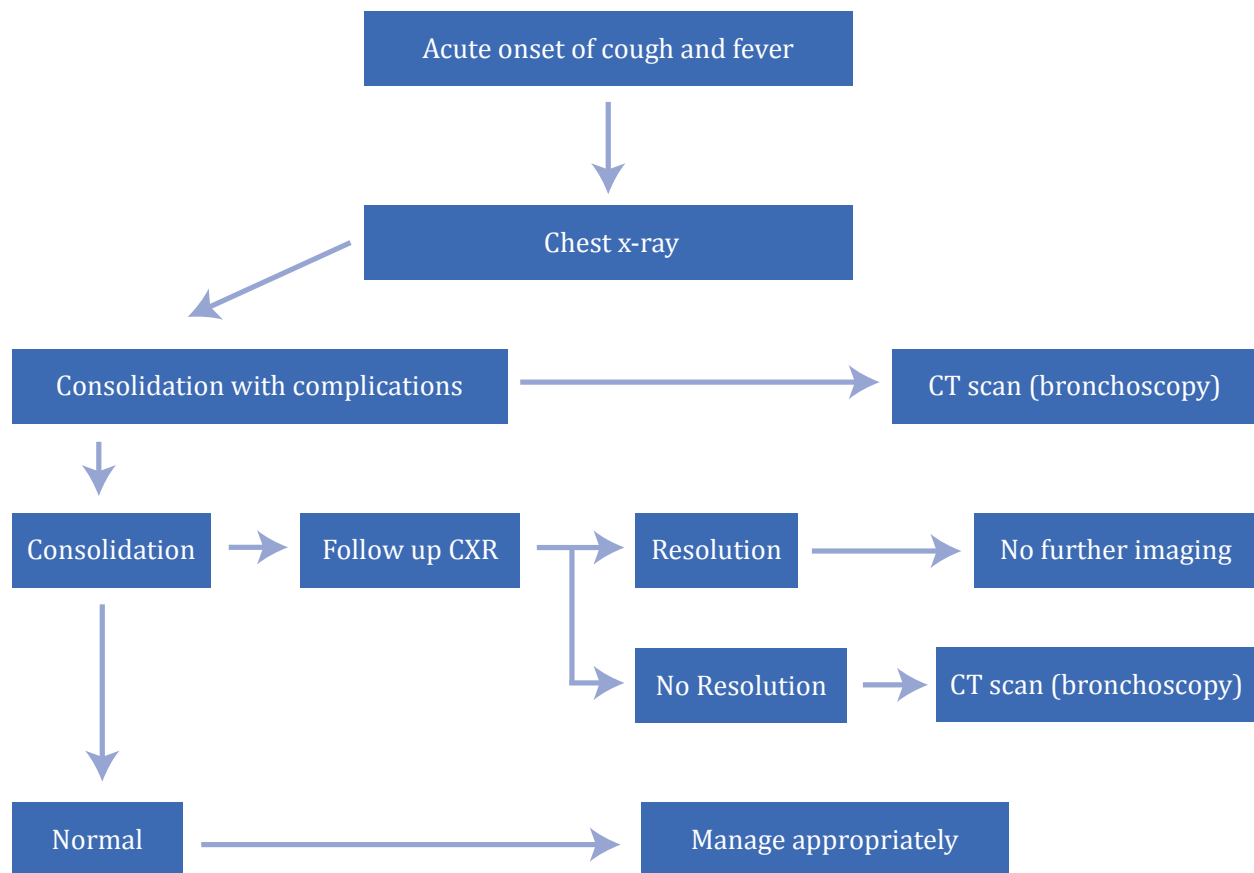
## EBR Case Scenario II

**Problem:** 55-year-old male presenting with one-week productive cough, weakness and febrile.

This case scenario has a high pre-test probability for community-acquired pneumonia. A review of the common methods of radiological investigations that are available will again demonstrate many different investigative possibilities: Plain film x-ray of the chest or computed tomography scans. Ultrasonography is not indicated, as it is unable to visualize lung tissue other than pleurae. From the data in Figure 6, we can conclude that a plain film x-ray of the chest would be the first-line approach to imaging the thoracic region in this patient. The radiation dose that the patient experiences is only 0.7mSv, which is classified as low. Also, according to the ACR Appropriateness

Criteria, plain film chest x-ray is most appropriate for investigating such a clinical presentation in a patient older than 40 years of age (33).

A plain film chest x-ray is a widely-used, cost-effective procedure that can assess the extent of consolidation of lung tissue. It can also demonstrate associated findings, such as pleural effusions, and the presence of underlying pathology, such as a bronchogenic carcinoma or bronchiectasis. Computed tomography can be used to assess the associated complications such as empyema. However, due to the substantially higher cost and complexity of the CT scan, the plain film chest x-ray is usually the method of preference (35). CT scans are employed in situations where chest x-ray findings imply more complicated pathology.



**Figure 6-** *Diagnosis cough and fever (33).*

## 12. APPENDIX 2: TEST OF IMPORTANT CONCEPTS

### PART 1 – MULTIPLE CHOICE:

- 1) Of the imaging modalities below, which do not use ionizing radiation? Choose all that are applicable.
  - a. Mammography
  - b. Plain Film Radiography
  - c. CT
  - d. SPECT
  - e. Fluoroscopy
  - f. MRI
  - g. Ultrasound
  - h. Digital Radiography
  - i. PET
- 2) Of the imaging modalities below, which use x-rays? Choose all that are applicable.
  - a. Mammography
  - b. Plain Film Radiography
  - c. CT
  - d. SPECT
  - e. Fluoroscopy
  - f. MRI
  - g. Ultrasound
  - h. Digital Radiography
  - i. PET
- 3) X-rays and  $\gamma$ -rays are both examples of ionizing radiation.
  - a. True
  - b. False
- 4) X-rays are used in nuclear medicine techniques (PET and SPECT).
  - a. True
  - b. False
- 5) A patient who was imaged using a modality that employs x-rays remains radioactive after the examination is terminated.
  - a. True
  - b. False
- 6) The biological effects of ionizing radiation are classified into stochastic and deterministic categories by the ICRP. Stochastic effects are:
  - a. Effects whose severity increases with dose
  - b. Effects whose probability increases with dose
- 7) When a patient is imaged using ionizing radiation, we are generally concerned about the deterministic effects.
  - a. True
  - b. False
- 8) The natural annual effective background dose is on the order of:
  - a. 1 – 10 mSv
  - b. 1 – 10 Sv
- 9) If you ensure that proper measures are taken to avoid unnecessary ionizing radiation exposures to patients, then you are following this principle:
  - a. ICRP
  - b. BEIR
  - c. ALARA
  - d. LAR
- 10) If a patient has aneurysm clips, which of the following imaging modalities should be avoided?
  - a. CT
  - b. MRI

### PART 2 – SHORT ANSWER:

- 11) Explain why the lungs appear black on a radiograph while the bones appear white.
- 12) List some possible ways of minimizing radiation exposure.
- 13) Summarize the effects of radiation in-utero.
- 14) Discuss some areas where ultrasound imaging would not be the modality of choice.

## **SOLUTIONS:**

- 1) f. MRI  
g. Ultrasound (see Section 2)
- 2) a. Mammography  
b. Plain Film Radiography  
c. CT  
e. Fluoroscopy  
h. Digital Radiography (see Section 2)
- 3) a. True (see Section 1)
- 4) b. False (see Section 2)
- 5) b. False (see Section 2)
- 6) b. Effects whose probability increases with dose (see Section 3.2)
- 7) b. False (see Section 3.2)
- 8) a. 1 – 10 mSv (see Section 3.3)
- 9) c. ALARA (see Section 3.3)
- 10) b. MRI (see Section 6.2)
- 11) (see Section 2)
- 12) (see Section 4)
- 13) (see Section 5)
- 14) (see Section 6.1)

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