Chapter 3
Medical Imaging Modalities and Digital Images

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Contents

3.1 Introduction

3.1.1 Special Aspects of Medical Images

Medical imaging technologies enable views of the internal structure and function of the human body. Information obtained from the various modalities can be used to diagnose abnormalities, guide therapeutic procedures, and monitor disease

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treatment. Medical images have unique performance requirements, safety restrictions, characteristic attributes, and technical limitations that often make them more difficult to create, acquire, manipulate, manage, and interpret. Some of these contributing factors include:

- Complexity of imaging situations:
  - Equipment size and available space,
  - Inaccessibility of the internal structures of the body to measurement,
  - Patient positioning,
  - Patient illness,
  - Procedure practicality.
- Variability of the data between patients; for example, between normal and abnormal anatomy and physiology, within normal ranges, and within the same patient at different times or body positions.
- Effect of imaging transducer on the image, including artifacts created by the imaging method or by something in the patient's body. A major source of artifact in images of living systems is **motion**.
- Safety considerations, patient discomfort, procedure time, and cost–benefit trade-offs.

DEFINITION: Artifact

Any component of the image that is extraneous to the representation of tissue structures; can be caused by a technique, technology, hardware, or software error.

3.1.2 Medical Imaging Terminology

- **Medical Imaging Hierarchy:** Patient – Examination (Study) – Series (Sequence) – Image. For example, a patient may undergo an imaging examination, also called a study, such as computed tomography (CT) of the abdomen. This study may include several sequences (a.k.a. series), such as a set of images with contrast and a set without contrast. A sequence or series may consist of a single image or multiple images.

CHECKLIST: Medical Imaging Hierarchy

1. Patient
2. Study or Examination
3. Series, Sequence or View
4. Image
5. Pixel

- Modalities can be characterized by whether their energy source uses **ionizing radiation** such as for radiography, fluoroscopy, mammography, CT, and nuclear medicine or nonionizing radiation such as for ultrasound and magnetic resonance imaging (MRI).
- **Projection** (planar) imaging, such as projection radiography in which X-rays from a source pass through the patient and are detected on the opposite side of the body,

produces a simple two-dimensional (2-D) shadow representation of the tissues lying between the source and the detector. Each point in the image has contributions from all objects in the body along a straight line trajectory through the patient. Overlapping layers of tissues can make planar imaging difficult to interpret.
- **Tomographic** (cross-sectional) imaging modalities include CT, MRI, and ultrasound. In CT, for example, the X-ray source is tightly collimated to interrogate a thin transverse section through the body. The source and detectors rotate together around the patient producing a series of one-dimensional projections at a number of different angles. The projection data are mathematically reconstructed to create a 2-D image of a slice through the body. Digital geometric processing can be used to generate a three-dimensional (3-D) image of the inside of objects from a series of 2-D image slices taken around a single axis of rotation. Historically, images have been generated in the axial (transverse) plane that is orthogonal to the long axis of the body. Today's modern scanners can reformat the data in any orientation (orthogonal or oblique to the body axis) or as volumetric representations due to the ability of modern scanners to acquire isotropic (equal dimensions in the x-, y- and z-planes) voxels.
- Medical modalities produce representations of anatomical (**structural**) or molecular/physiological (**functional**) information of the imaged body parts. For example, X-ray images are representations of the distribution of the linear attenuation coefficients of tissues and are largely images of anatomy or the structural nature of the tissues in the body. Radioisotope imaging of nuclear medicine produces images of the distribution of chemical, molecular, or physiological function of the tissue. Some modalities, such as ultrasound, can provide other types of functional measures, such as speed of blood flow through vessels.

DEFINITION: Ionizing Radiation

Radiation capable of producing energetically charged particles that move through space from one object to another where the energy is absorbed. Radiation is potentially hazardous if used improperly.

KEY CONCEPT: Imaging Modalities

Modalities can be characterized by their energy source as invasive (using ionizing radiation) or noninvasive. They are acquired in 2-D planar projection mode or tomographic cross section; and produce images representative of anatomical structure and/or physiological or molecular function.

KEY CONCEPT: X-Ray Attenuation

Attenuation of an X-ray beam is largely a function of tissue radiodensity. Bone, for example, has a higher attenuation coefficient than soft tissue. In a radiograph of the chest, bony structures highly attenuate (or absorb) X-rays, passing less signal through the body to the detector; whereas soft tissues are less attenuating, passing more signal through to the detector. Air is least attenuating, and thus high signal hits the detector and is represented as black in most images; no signal hitting the detector is usually represented as white. In a chest radiograph, the air spaces in the lungs appear black, soft tissues are lighter gray, and the bony ribs and spine are white.

3.2 Diagnostic Imaging Modalities

For each diagnostic modality given below, the energy source and detector used in image formation are listed along with the tissue characteristic or attribute represented by the modality. Advantages and disadvantages for each are included.

3.2.1 Projection Radiography

- Source: X-rays; ionizing radiation; part of the electromagnetic spectrum emitted as a result of bombardment of a tungsten anode by free electrons from a cathode. The source passes through the patient and X-rays are detected on the opposite side of the body.
- Analog detector: fluorescent screen and radiographic film; historical and rarely used today in developed countries with access to digital technology.
- Digital detector: **computed radiography (CR)** uses a photostimulable or storage phosphor imaging plate; direct **digital radiography (DR)** devices convert X-ray energy to electron–hole pairs in an amorphous selenium photoconductor, which are read out by a thin-film transistor (TFT) array of amorphous silicon (Am-Si). For indirect DR devices, light is generated using an X-ray sensitive phosphor and converted to a proportional charge in a photodiode (e.g., cesium iodide scintillator) and read out by a charge-coupled device (CCD) or flat panel Am-Si TFT array.
- Image attributes: variations in the **grayscale** of the image represent the X-ray attenuation or density of tissues; bone absorbs large amounts of radiation allowing less signal to reach the detector, resulting in white or bright areas on the image; air has the least attenuation causing maximum signal to reach the detector, resulting in black or dark areas of the image.

- Advantages: fast and easy to perform; equipment is relatively inexpensive and widely available; low amounts of radiation; high spatial resolution capability. Particularly useful for assessing the parts of the body that have inherently high contrast resolution but require fine detail such as for imaging the chest or skeletal system.
- Disadvantages: poor differentiation of low contrast objects; superposition of structures through projection of a 3D object (the patient) onto a 2D image makes image interpretation difficult; uses ionizing radiation.

3.2.2 Mammography and Tomosynthesis

- Source: X-rays; ionizing radiation as in other projection radiography examinations.
- Detector: analog film may still be used in some countries. However, specialty Digital Detectors made as dedicated systems for imaging the breast are available and in widespread use. CR can be used as a direct replacement for screen-film systems as it can be used with existing acquisition system infrastructure. Direct DR devices include CCD multi-detectors, slot-scanning CCD detectors, and Am-Si flat panel detectors. All acquire images at higher spatial resolution than for other digital projection radiographs. **Digital Breast Tomosynthesis (DBT)**

FURTHER READING: Physics of Medical Imaging

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HYPOTHETICAL SCENARIO: Radiation Dose

Exposure to radiation at excessive doses can damage living tissue. Note however that the radiation exposure for a chest X-ray is equivalent to the amount of radiation exposure one experiences over a 10-day period from natural surroundings alone.

devices generate 2D and pseudo-3D images of the breast by acquiring multiple 2D slice images at different angles as the X-ray source moves in an arc around the breast.

- Image attributes: variations in the grayscale of the image represent the X-ray attenuation or density of tissues; with calcifications appearing as white or bright areas in the image.
- Advantages: fast and easy to perform; equipment is relatively inexpensive and widely available; low amounts of radiation; high spatial resolution capability. Tomosynthesis has the advantage of improved visibility of superimposed structures as a pseudo-3D image and has been shown to assist in the detection of early breast cancers and decrease the call-back rate for additional tests.
- Disadvantages: traditional 2D mammography suffers from superposition of overlapping structures; uses ionizing radiation; image file sizes are large for mammograms and for breast digital tomosynthesis, and both require specialty display workstations.

KEY CONCEPT: Special Requirements for Mammography

Mammography has been among the last modalities to transition to digital acquisition, storage, and display. This may be due to a number of its special requirements including high spatial resolution (to enable visibility of fine spiculations and microcalcifications), high contrast resolution (to increase conspicuity among subtle differences in soft tissue, and the ability to visualize dense and overlapping tissues). Radiation dose must be kept low to be effective as a screening examination. Traditional mammography also has special display requirements that must accommodate very high spatial resolution (5 MegaPixel), ease of simultaneous display of the basic four-view examination (bilateral craniocaudal (CC) and mediolateral oblique (MLO) views) in addition to the ability to view prior historical examinations alongside the current study. The ability to apply masking and traditional markups is also required. Mammography detectors whether CR or DR have higher spatial resolution capabilities (50 to 100 micron pixel sizes) than for other projection radiography studies (200 micron pixel size), are sampled at roughly twice the frequency, and therefore generate much larger digital files (approximately 40 MB or more per image). Typical breast tomosynthesis examinations can range from approximately 450 MB to 3 GB, and require specialty acquisition and display devices. Computer-aided detection (CAD) algorithms are typically used with digital mammography and require either an additional stand-alone or integrated CAD system. Mammography is highly regulated and specific laws of the Mammography Quality Standards Act (MQSA) must be met with regard to acquisition and display workstation implementations [1].

3.2.3 Fluorography

SYNONYMS: Fluoroscopy

- Fluorography
- Fluoro
- Cine
- Radiofluoroscopy
- RF

- Source: continuous low-power X-ray beam; ionizing radiation.
- Detector: X-ray image intensifier amplifies the output image.
- Image attributes: continuous acquisition of a sequence of X-ray images over time results in a real-time **X-ray video**; may use inverted grayscale (white for air; black for bones).
- Advantages: can image anatomic motion and provide real-time image feedback during procedures. Useful for monitoring and carrying out studies of the gastrointestinal tract, arteriography, and interventional procedures such as positioning catheters.
- Disadvantages: lower image quality than static projection radiographs; typically only a subset of key images are archived.

3.2.4 Computed Tomography (CT)

- Source: collimated high-power X-ray beam; X-ray tube and detector array rotate around the patient.
- Detector: early sensors were scintillation detectors with photomultiplier tubes excited by sodium iodide (NaI) crystals; modern detectors are solid-state scintillators coupled to photodiodes or are filled with low-pressure xenon gas. Data is collected and stored in a "sinogram" matrix from which tomographic slices are reconstructed using a "filtered back-projection" or "adaptive statistical iterative reconstruction" (ASIR) algorithm [1].
- Image attributes: thin transverse cross-sectional sections of the body are acquired representing the absorption pattern or X-ray attenuation of each tissue. Absorption values are expressed as **Hounsfield Units**, also called CT numbers, with water as the zero frame-of-reference. To highlight certain tissues, CT images are dynamically viewed with different Window (window width) and Level (window level) presets. Window width reflects the range of grayscales displayed with all pixels below the range appearing black and those pixels above the range appearing white in the image. Window reflects image contrast. Window level defines the center value of the width and reflects the perceived brightness in the image. Increasing the window width results in an image with perceived decrease in contrast (e.g., bone window/level ~2000/300, lung window/level ~1500/−700). Decreasing the window width results in an image with perceived increased contrast (e.g., abdominal window/level ~400/40, brain window/level ~80/35, liver window/level 200/50) [1].

KEY CONCEPT: Window and Level

Cross-sectional imaging modalities produce 12-bit data (4096 potential values) or more for each pixel. The human eye can only distinguish between 700–900 different shades of gray, and most display monitors are capable of producing only 8-bit grayscale (256 grays). Thus, when viewing images, the radiologist will focus on a portion of the data that falls within a defined range (the window). Any pixel with a value below the window will be displayed as black, and any pixel with a value higher than the window will be displayed as white. Pixels with values within the window will have different shades of gray. You could define the window by its upper and lower values, but it is more commonly defined by its center point (level) and extent (width). Adjusting the window on the fly is a routine part of image interpretation.

- Advantages: good contrast resolution allowing differentiation of tissues with similar physical densities; tomographic acquisition eliminates the superposition of images of overlapping structures; advanced scanners can produce images that can be viewed in multiple planes (multiplanar reformats) or as volumes due to the ability to acquire isotropic voxels using current multidetector row technology scanners. Any region of the body can be scanned; has become diagnostic modality of choice for a large number of disease entities; useful for tumor staging.
- Disadvantages: high cost of equipment and procedure; high dose of ionizing radiation per examination; artifacts from high contrast objects in the body such as bone or metallic devices; can generate large study file sizes for examinations such as CT angiography, cardiac CT, and perfusion studies (e.g., for stroke) [1].

DEFINITION: Hounsfield Unit

CT number representing absorption values of tissues; expressed on a scale of −1000 units for the least absorbent (air) to the maximum X-ray beam absorption of bone (+3000 for dense bone). Water is used as a reference material for determining CT numbers and is, by definition, equal to 0. Set ranges of CT numbers can designate tissue type, and differences in tissue Hounsfield units can indicate abnormal findings and/or pathology.

3.2.5 Magnetic Resonance Imaging (MRI) [1]

- Source: **high-intensity magnetic field** (1.5–3 Tesla and some 7T); typically, helium-cooled superconducting magnets are used today; nonionizing; gradient coils turn radiofrequency (RF) pulses on/off at different time sequences based on the desired image contrast and anatomical presentation; example **pulse sequences** include spin echo, fast spin echo, inversion recovery, STIR, FLAIR, gradient echo, etc. Manipulable acquisition parameters include TR (repetition time), TE (echo time), TI (inversion time), flip angle, and slice thickness.
- Detector: phased array receiver coils capable of acquiring multiple channels of data in parallel.

- Image attributes: produces images of the body by utilizing the magnetic properties of protons in tissues, predominately hydrogen (H^+) in water and fat molecules; the response of magnetized tissue when perturbed by an RF pulse varies between tissues and is different for pathological tissue as compared to normal. T1, T2, proton density, blood flow, perfusion, and diffusion are some of the tissue characteristics exploited by MRI to manipulate tissue contrast.
- Advantages: **nonionizing radiation**, originally called nuclear magnetic resonance (NMR) but because the word "nuclear" was associated with ionizing radiation, the name was changed to emphasize the modality's safety; can image in any plane; has excellent soft tissue contrast detail; visualizes blood vessels without contrast; no bony artifact since no signal from bone; particularly useful in neurological, cardiovascular, musculoskeletal, and oncological imaging.
- Disadvantages: high purchase and operating costs; lengthy scan time; more difficult for some patients to tolerate; susceptible to motion artifact; poor images of lung fields and bone; inability to show calcification; contraindicated in some patients with **pacemakers, hearing aids or metallic foreign bodies**; safety issues must be adhered to for hospital personnel working in the vicinity of MRI scanners.

KEY CONCEPT: MRI Procedure

The patient is subjected to a magnetic field, which forces the H^+ nuclei in tissues to align with the magnetic field. An excitation pulse of radiofrequency is applied to the nuclei, which perturbs them from their position (through energy absorption). When the pulse is removed, the nuclei return to their original state releasing energy (re-emission), which can be measured and converted to a grayscale image. Multiple pulse sequences are typically used in combinations specific to the diagnostic requirements.

3.2.6 Nuclear Medicine and Positron Emission Tomography (PET)

- Source: X-ray or γ-ray emitting radioisotopes are injected, inhaled, or ingested; most common isotopes are technetium-99, thallium-201, and iodine-131.
- Detector: gamma camera with NaI scintillation crystal measures the radioactive decay of the active agent; emitted light is read by photomultiplier tubes; pulse arithmetic circuitry measures number and height of pulses. Further, these pulses are converted to an electrical signal that is subsequently processed into a grayscale image.
- Image attributes: metabolic, chemical, or physiological interactions of the radioisotope are measured. The radioisotope chemical is distributed according to physiological function so the image primarily represents **functional information**; however, since function is distributed in the physical structures, recognizable anatomical images are produced, though at a lower quality.

- Advantages: measures targeted specific chemical-physiologic tissue function; valuable diagnostic tool particularly for imaging infarcts in the cardiovascular system, imaging uptake at sites of increased bone turnover as in arthritis and tumors, assessing the aggressiveness of small tissue nodules, and in oncologic assessment.
- Disadvantages: high cost of some radioisotopes; ionizing radiation; long scan times; patients must wait for the radiotracer to distribute before being imaged.

DEFINITION: SPECT

Single-Photon Emission Computed Tomography; a tomographic slice is reconstructed from photons emitted by the radioisotope in a nuclear medicine study.

DEFINITION: PET

Positron Emission Tomography uses cyclotron-produced positron-emitting isotopes including oxygen, carbon, nitrogen, and fluorine, enabling accurate studies of blood flow and metabolism (as with fluorine-19 fluoro-deoxyglucose (FDG)). Positron isotopes are short-lived positively charged antimatter electrons. The main clinical applications are in the brain, heart, and tumors.

3.2.7 Ultrasound

- Source: high-frequency sound waves produced by a transducer made of a piezoelectric crystal.
- Detector: the source **transducer** also functions as a receiver of reflected sound and converts the signal into an electric current, which is subsequently processed into a grayscale image.
- Image attributes: sound waves travel through the body, are affected by the different types of tissues encountered and reflected back; a real-time moving image is obtained as the transducer is passed across the body.
- Advantages: very low cost; safe nonionizing energy source; can scan in any plane; equipment is portable and can be used for bedside imaging; particularly useful for monitoring pregnancy, imaging the neonatal brain, visualizing the uterus, ovaries, liver, gallbladder, pancreas, and kidneys, confirming pleural effusions and masses, and assessing the thyroid, testes, and soft-tissue lesions; increasing use as the first imaging modality for triage at the point-of-care.
- Disadvantages: **operator-dependent**; poor visualization of structures underlying bone or air; scattering of sound through fat yields poor images in obese patients. Not all PACS (picture archiving and communication system) display stations are capable of displaying ultrasound video clips thus requiring specialty ultrasound “mini-PACS.”

KEY CONCEPT: Doppler Ultrasound

A technique to examine moving objects in the body. Blood flow velocities can be measured using the principle of a shift in reflected sound frequency produced by the moving objects. Can be used to image the cardiac chambers and valves of the heart, arterial flow, particularly to assess the carotids and peripheral vascular disease, and venous flow studies for the detection of deep-vein thrombosis.

3.2.8 Visible Light

- Source: visible light spectrum; electromagnetic radiation wavelengths between approximately 380 (violet) to approximately 750 (red) nanometers.
- Detector: charge-coupled devices (CCD) and video cameras. Mobile phones may have adequate image quality but have security issues.
- Image Attributes: wavelength dictates the "color" while intensity, propagation direction, contrast, and polarization contribute to the perceived appearance.
- Advantages: uses a noninvasive energy source; visible light imaging is used in light microscopy for pathological diagnosis, hematology, dermatology to photograph skin lesions, gastroenterology (colonoscopy/endoscopy), ophthalmology to image the retina, and during surgical procedures.
- Disadvantages: has limited ability to penetrate tissues deeply like the energies used in radiological imaging.

3.3 Digital Images

3.3.1 Definition

- A continuous image $f(x,y)$ is a 2-D light intensity function f at spatial coordinates x,y; the value f at location x,y is proportional to the brightness or grayscale of the image at that point.
- A digital image is an image $d(x,y)$ that has been **discretized** (digitized) both in space (physical location) and in amplitude (gray level); it can be considered as a matrix whose row and column indices identify a point x_1, y_1 in the image, and the corresponding matrix element value $d(x_1, y_1)$ identifies the gray level at that point. Elements in the digital array are called **pixels** (short for "picture elements") and each is represented by a numerical value. Three-dimensional images consist of **voxels** ("volume elements").
- The **matrix size** is the product of the number of pixels in each dimension.

KEY CONCEPT: Pixels and Voxels

A pixel is the smallest discrete element in a digital image and it has a single color value. A voxel is a three-dimensional picture element in a 3-D image and represents a volumetric sample of the body.

3.3.2 Digital Image Formation

- To be suitable for computer processing, an image function must be digitized both spatially and in amplitude. Image sampling is the digitization of the spatial coordinates and is related to pixel size, reflective of matrix size and affects spatial resolution.
- Image gray level quantization is digitization of the amplitude or brightness, is determined by computer bit depth, and is reflected in the image contrast resolution.
- The process of digital image production includes scanning of the analog image line-by-line to obtain a continuous analog signal representing the variations in image brightness, followed by dividing the analog signal into individual pixels in a process known as spatial sampling, which is typically performed in equal intervals; this is followed by converting the amplitude into a digitized numerical pixel value in the process of contrast quantization; lastly, an analog-to-digital (ADC) converter turns the quantized level into binary code (Fig. 3.1).

3.3.3 Image Quality Factors

- **Spatial resolution** limits sharpness (edges separating objects in the image) or visibility of fine detail and is a function of sampling that affects matrix and pixel size. Since each pixel can have only one numerical value, it is not possible to observe any anatomical detail within a pixel. More frequent sampling that results in smaller pixels (larger matrix sizes) provides better visibility of fine detail and a better quality higher spatial resolution image. If images are insufficiently sampled, the poorer resolution images may have a characteristic blockiness or checkerboard artifact.
- **Contrast resolution** limits differentiation of detail within and between objects and is a function of the bit depth used to represent the grayscale quantization. Insufficient quantization can result in false contouring or ridges in which smoothly varying regions of an object within the image become undifferentiable.
- **The total resolution of a digital image is the combination of the spatial resolution and the contrast resolution.** An image file size is equal to the product of the matrix size (number of rows times number of columns) times the number of

KEY CONCEPT: Spatial Resolution vs. Contrast Resolution

Spatial resolution of an image limits visibility of fine detail and is reflected in matrix and pixel size. High spatial resolution enables visibility of small objects. Conventional X-rays and mammography have excellent spatial resolution. Contrast resolution limits the ability to distinguish between differences in object intensities in an image and is represented by the number of different colors or grays in the image. High contrast resolution enables differentiation of tissues with similar imaging characteristics. CT and MRI exhibit high contrast resolution.

8-bit bytes required to represent the image bit depth. For example, a CT slice is typically 512 rows by 512 columns and the grayscale is represented by 16 bits. It requires 2 bytes to account for 16 bits of grayscale, and therefore, a CT slice file size is $512 \times 512 \times 2 = 524{,}288$ bytes or approximately half a megabyte (MB). A single-view chest radiograph is approximately 10 MB.
- **Noise** is a characteristic of all medical images; increased noise can lower image quality; noise is sometimes referred to as image mottle and gives the image a textured, snowy, or grainy appearance that can degrade visibility of small or low contrast objects. The source and amount of image noise depend on the imaging method; nuclear medicine images generally have the most noise, followed by MRI, CT, and ultrasound; radiography produces images with the least amount of noise.

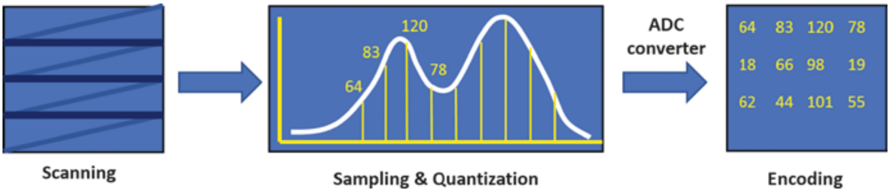

Fig. 3.1 The digital image formation process including scanning, sampling and quantization, and analog-to-digital conversion

KEY CONCEPT: Intrinsic Image Quality

A trade-off between spatial resolution and contrast or density resolution; an image with intrinsically poor spatial resolution can be made visually sharper by enhancing the contrast.

PEARLS

- Medical images have special features that make them difficult to create, acquire, manipulate, manage, and interpret. Complexities include human variability, performance requirements, safety considerations, motion artifacts, technical limitations, and cost.
- Diagnostic imaging modalities are categorized by their sources (ionizing or nonionizing radiation), acquisition mode (projection or cross-section), and tissue property measured (anatomic structure or molecular function).
- Medical imaging hierarchy includes patient, examination (study), series (sequence), image, and pixel.
- Digital images are discretized (digitized) by sampling in space (location) and quantizing in contrast (grayscale).
- Spatial resolution limits sharpness or visibility of fine detail and edges in the image; it is a function of sampling that affects matrix and pixel size.
- Contrast resolution limits the number of different colors or grayscales represented in the image and is a function of quantization bit depth.

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Suggested Reading

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Self-Assessment Questions

1. Which of the following is the most significant source of artifact in medical images?

   (a) Human variability
   (b) Patient positioning
   (c) X-ray dose
   (d) Subject motion
   (e) Safety considerations

2. Which of the following imaging modalities use ionizing radiation as its source?

   (a) Magnetic resonance imaging
   (b) Computed tomography
   (c) Ultrasound imaging
   (d) All of the above
   (e) None of the above

3. Which of the following modality is most affected by the skill of the operator?

   (a) Projection radiography
   (b) Ultrasound
   (c) Computed tomography
   (d) Magnetic resonance imaging
   (e) Positron emission tomography

4. In the formation of a digital image, sampling affects which of the following?
   (a) Visible fine detail
   (b) Image matrix size
   (c) Spatial resolution
   (d) All of the above
   (e) None of the above
5. Which imaging modality provides higher spatial resolution?
   (a) Chest projection radiograph
   (b) Chest CT