

**CURRICULUM
UPDATED COPY
December 2018**

Diagnostic Radiology Residents Physics Curriculum

Prepared by

**Imaging Physics Curricula Subcommittee
AAPM Subcommittee of the Medical Physics Education of Physicians Committee**

UPDATED – December 2018

Supported by: AAPM Education Council

The Diagnostic Radiology Residents Physics Curriculum was first published in 2007. Since that time it has been reviewed and updated to maintain its relevance and to incorporate the many advancements in imaging technology that have occurred. This current edition was reviewed and updated in 2018 by the Imaging Physics Curricula Subcommittee of the American Association of Physicists in Medicine. Not all modules were updated since the previous version. Membership of the subcommittee consists of:

William F. Sensakovic, PhD (Subcommittee Chair and Module 5 Editor)
Karen L. Brown, MHP (Subcommittee Vice Chair and Module 11 Editor)

Jon A. Anderson, PhD (Module 1 Co-editor)
Trevor Andrews, PhD (Module 13 Co-editor)
Richard H. Behrman, PhD (Module 10 Co-editor)
Christina L. Brunnquell, PhD
Bennett S. Greenspan, MD (Module 14 Co-editor)
Ping Hou, PhD (Module 13 Co-editor)
Mary E. Moore, MS
Adel A. Mustafa, PhD (Module 12 Editor)
Jonathon A. Nye, PhD (Module 14 Co-editor)
Anshuman Panda, PhD
Ronald Price, PhD (Module 1 Co-editor)
Sameer Tipnis, PhD
Nathan E. Yanasak, PhD
David A. Zamora, MS (Module 8 Editor and Module 10 Co-editor)
Jie Zhang, PhD (Module 9 Editor)

Special Thanks To:
Kalpana Kanal, PhD

TABLE OF CONTENTS

<u>Module 1 – Basic Science – Structure of the Atom, Electromagnetic (EM) Radiation, and Particulate Radiation</u>	6
<u>Module 2 – Interactions of Ionizing Radiation with Matter</u>	14
<u>Module 3 – Radiation Units</u>	21
<u>Module 4 – X-Ray Production</u>	26
<u>Module 5 – General Imaging and Informatics Concepts</u>	32
<u>Module 6 – Biological Effects of Ionizing Radiation</u>	45
<u>Module 7 – Radiation Protection and Associated Regulations</u>	52
<u>Module 8 – General Radiography - Projection Imaging Concepts and Detectors</u>	62
<u>Module 9 – Mammography</u>	77
<u>Module 10 – Fluoroscopy and Interventional Imaging</u>	87
<u>Module 11 – Computed Tomography</u>	98
<u>Module 12 – Ultrasound</u>	109
<u>Module 13 – Magnetic Resonance Imaging</u>	123
<u>Module 14 – Nuclear Medicine</u>	143

Preface

The purpose of this curriculum is to outline the breadth and depth of scientific knowledge underlying the practice of diagnostic radiology that will aid a practicing radiologist in understanding the strengths and limitations of the tools in his/her practice. This curriculum describes the core physics knowledge related to medical imaging that a radiologist should know when graduating from an accredited radiology residency program.

Although this curriculum was not developed specifically to prepare residents for the American Board of Radiology (ABR) examination, it is understood that this is one of the aims of this curriculum. This curriculum is designed to list the fundamental radiologic concepts and imaging methods a practicing radiologist should understand. While specific pathology and organ systems are not addressed directly within the curriculum, the educator needs to associate the concepts within the modules continuously in different organ systems to assure that the clinical applications are evident.

This curriculum contains 14 modules covering imaging physics. The first seven modules cover radiation physics, safety, regulation, and biology. The remaining seven modules are dedicated to specific modalities utilized in radiology. Each module presents its content in three sections: (1) learning objectives, (2) curriculum, and (3) Q&A.

The first section of each module presents the learning objectives for the module. These learning objectives are organized into two subsections: (1) fundamental knowledge relating to module concepts and (2) specific clinical applications of this knowledge with examples of relevant clinical problems related to the information.

The second area within each module presents the curriculum that delineates the concepts the module addresses. The curriculum may be used as an outline for a course in imaging physics. Not all areas of each curriculum module need be taught with the same emphasis or weight, as long as the student can demonstrate an understanding of the educational objectives and solve clinically relevant problems. The curriculum is presented as a guide to the instructor providing specific topic details that may be needed to cover a subject more thoroughly.

After each item in the curriculum is a number in brackets. This is a priority score as voted on by members of the subcommittee. Although the committee believes all topics within the curriculum should be understood by a radiology resident, we also recognize educators often have limited time in which to teach. The priority score can be utilized by educators with limited teaching time to prioritize subjects. The scores are interpreted as follows: 3-Necessary, 2-Important, 1-If there is time. *In the view of this subcommittee it is NOT acceptable to skip low-scoring topics or expect them to be less represented on an exam. If a topic cannot be taught by the educator, it remains the resident's responsibility to learn that information themselves.*

The third area within each module gives examples of questions and answers based on the content in the module to give the resident and educator an idea about the type of questions that could be asked on the topic. The questions are not based on recalls of old American Board of Radiology examination questions. Any similarity with the past or current ABR examination is purely coincidental.

Selected Useful References:

The following are references that members of the subcommittee have found particularly useful for teaching. This list should not be interpreted as exhaustive and should not be viewed as an official endorsement by AAPM or the subcommittee for those materials. Other resources of equal or greater value may be available. Topic-specific references can also be found in each module:

1. Bushberg JT, Seibert JA, Liedholdt EM, et al. The Essential Physics of Medical Imaging, 3rd ed. Lippincott Williams & Wilkins, 2012.
2. Huda W. Review of Radiologic Physics, 4th ed. Wolters Kluwer, 2016.
3. Bushong SC. Radiologic Science for Technologists: Physics, Biology, and Protection, 11th ed. Elsevier, 2017.
4. RSNA/AAPM Radiology Physics Educational Modules. <https://www.rsna.org/en/education/trainee-resources/physics-modules>, Last Accessed 12/11/2018.
5. RadiologyInfo.org. <https://www.radiologyinfo.org/>. Last Accessed 12/11/2018.
6. RadioGraphics American Association of Physicists in Medicine Diagnostic Radiology Residents Physics Curriculum Article Index. <https://pubs.rsna.org/page/radiographics/aapm-physics>. Last Accessed 12/11/2018.

Module 1: Basic Science – Structure of the Atom, Electromagnetic (EM) Radiation, and Particulate Radiation

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Describe the components of the atom.
2. Explain the energy levels, binding energy, and electron transitions in an atom.
3. For the nucleus of an atom, describe its properties, how these properties determine its energy characteristics, and how changes within the nucleus define its radioactive nature.
4. For an atom, describe how its electron/nuclear structure and associated energy levels define its radiation-associated properties.
5. Explain how different transformation (“decay”) processes within the nucleus of an atom determine the type of radiation produced and the classification of the nuclide.
6. Describe the wave and particle characteristics of electromagnetic (EM) radiation.
7. Within the EM radiation spectrum, identify the properties associated with energy and the ability to cause ionization.
8. Identify the different categories and properties of particulate radiation.

Clinical Applications and Problem-Solving:

1. Explain how the relative absorption of electromagnetic radiation in the body varies across the electromagnetic energy spectrum.
2. Introduce the concept of interactions of ionizing photons, e.g., in imaging detectors, biological effects, etc.
3. Give examples of types of EM radiation used in imaging in radiology and nuclear medicine.
4. Understand why particulate radiation is not used for diagnostic imaging.

Curriculum:

1. Basic Science
 - 1.1. Structure of the Atom
 - 1.1.1. Composition [3.0]
 - 1.1.1.1. Electrons [3.0]
 - 1.1.1.2. Nucleus [3.0]
 - 1.1.2. Electronic Structure [2.3]
 - 1.1.2.1. Electron Orbits [1.9]
 - 1.1.2.2. Orbital Nomenclature [1.6]
 - 1.1.2.3. Binding Energy [2.7]
 - 1.1.2.4. Electron Transitions [2.9]
 - 1.1.2.5. Characteristic Radiation [2.4]
 - 1.1.2.6. Auger Electrons [1.4]
 - 1.1.3. Nuclear Structure [2.9]
 - 1.1.3.1. Composition [2.4]
 - 1.1.3.2. Nuclear Force [1.0]
 - 1.1.3.3. Mass Defect [1.3]
 - 1.1.3.4. Binding Energy [2.9]
 - 1.1.3.5. Overview of Radioactive Decay [2.9]
 - 1.1.3.6. Isotopes and Isomers [2.7]

- 1.2. Electromagnetic (EM) Radiation [3.0]
 - 1.2.1. The Photon [3.0]
 - 1.2.1.1. Electromagnetic Quanta [2.0]
 - 1.2.1.2. Origin of X-rays, Gamma Radiation, and Annihilation Radiation [3.0]
 - 1.2.1.3. Properties of Photons [3.0]
 - 1.2.1.3.1. Energy Mass Equivalence [2.1]
 - 1.2.1.3.2. Speed [2.1]
 - 1.2.1.3.3. Energy [3.0]
 - 1.2.2. Electromagnetic Spectrum [2.7]
 - 1.2.2.1. Electric and Magnetic Components [2.3]
 - 1.2.2.2. Ionizing, e.g., X-rays, Gamma Rays [3.0]
 - 1.2.2.3. Non-Ionizing, e.g., RF (MRI), Visible Light [2.9]
- 1.3. Particulate Radiation [2.9]
 - 1.3.1. Electrons and Positrons [2.9]
 - 1.3.2. Heavy Charged Particles [1.4]
 - 1.3.2.1. Protons [1.1]
 - 1.3.2.2. Alpha Particles [1.7]
 - 1.3.3. Uncharged Particles [1.0]
 - 1.3.3.1. Neutrons [1.6]
 - 1.3.3.2. Neutrinos and Antineutrino [1.0]

Example Q&A:

Q1. Elements which have the same Z (atomic number) but different A (mass number) are called:

- A. Isobars
- B. Isomers
- C. Isotones
- D. Isotopes

Answer: D – Isotopes

Explanation: Isotopes are forms of the same element, and thus have the same atomic number Z (the number of protons), but have a different number of neutrons, thus different mass number A (neutrons plus protons). Isobars have the same A but different Z . Isomers have the same A and Z , but different energy states. Isotones have the same number of neutrons but different Z . Isotopes and isomers are common concepts in radiology.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q2. The mass number (A) of an atom is equal to the number of:

- A. Neutrons
- B. Protons
- C. Neutrons and protons
- D. Protons and electrons

Answer: C – Neutrons and protons

Explanation: The mass number is defined as the number of nucleons (protons and neutrons) in the atomic nucleus.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q3. The binding energy of an electron in the K-shell is:

- A. The energy the electron needs to stay in the K-shell
- B. The energy needed for an electron to make a transition from the K-shell to L-shell
- C. The energy needed for an electron to transition from the L-shell to K-shell
- D. The energy needed to remove an electron in the K-shell from the atom

Answer: D – The energy needed to remove an electron in the K-shell from the atom.

Explanation: The K-shell binding energy is the energy to ionize the atom by removing the K-shell electron.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q4. A proton is electrostatically repelled by:

- A. Electrons
- B. Neutrons
- C. Photons
- D. Neutrinos
- E. Alphas

Answer: E – Alphas

Explanation: As a proton, a positron, and an alpha particle are all positively charged particles (while an electron is negatively charged and a neutron is neutral), a proton will be repelled by both a positron and an alpha particle.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q5. Which of the following modalities uses only non-ionizing radiation to generate an image?

- A. Fluoroscopy
- B. Mammography
- C. MRI
- D. CT

Answer: C – MRI

Explanation: MRI uses radio waves, while all other modalities use ionizing radiation.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q6. Which of the following is an example of particulate radiation?

- A. Microwaves
- B. X-rays
- C. Alpha particles
- D. Gamma rays

Answer: C – Alpha particles

Explanation: Microwaves, x-rays, and gamma rays are all forms of electromagnetic radiation. Only alpha particles are particulate.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q7. A radiation detector records a reading when an unshielded detector is swept over a spill, but no reading when a shielded detector is swept over the spill. What does this tell us about the spilled substance?

- A. The substance is not radioactive since it did not register in both orientations.
- B. The substance emits high-energy photons since it only registered when unshielded.
- C. The substance emits particulate radiation or very low-energy photons since it only registered when unshielded.
- D. The substance has a very long half-life because the meter did not register when shielded.

Answer: C – The substance emits particulate radiation or very low-energy photons since it only registered when unshielded.

Explanation: Particulate or very low-energy photons will be absorbed in the shielding and will not register (or barely register) in the detector. When unshielded, the energy is deposited in the detector. Particulate radiation has a limited range and will not pass through a shielded detector.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Cherry, S.R., J.A. Sorenson, and M.E. Phelps. *Physics in Nuclear Medicine*, 4th ed. Philadelphia: Elsevier Saunders, 2012.

Q8. A person accidentally ingests an unknown radioactive substance that is subsequently permanently bound to his bony tissues (biological half life > 20 years). If this individual lives in close proximity to his or her family, which of the following types of radiation is the greatest safety concern for the family?

- A. Photons (>100 keV)
- B. Neutrinos
- C. Electrons (30 keV)
- D. Alpha particles

Answer: A – Photons (>100 keV)

Explanation: Low-energy electrons and alpha particles all have relatively short ranges in human tissue, and thus most or all of these particles will be absorbed by the person and will not reach the family to cause radiation damage. Neutrinos have very little interaction with tissue.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q9. Radionuclides used for nuclear medicine imaging must include one of the following emissions:

- A. Electrons
- B. Alpha particles
- C. Gamma rays
- D. Protons

Answer: C – Gamma rays

Explanation: Particulate radiations such as electrons, alphas and protons have a limited range in human tissue. The particles will be absorbed within the body and will not reach an external imaging detector. Gamma rays are more penetrating and undergo relatively fewer interactions within the body allowing detection by an external detector.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q10. The number of electrons in a neutral atom is the:

- A. Mass defect
- B. Mass number
- C. Atomic number
- D. Binding Energy

Answer: C – Atomic number

Explanation: The atomic number is defined to be the number of protons within the nucleus. For a neutral atom the number of negatively charged orbital electrons is equal to the number of positively charged protons in the nucleus.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q11. What is the likely result when an electron vacancy in the K-shell is filled by an electron from the L-shell?

- A. Annihilation radiation
- B. Gamma ray
- C. Characteristic x-ray
- D. Neutrino

Answer: C – Characteristic x-ray

Explanation: Electron transition between atomic energy shells results in the emission of a characteristic x-ray photon. The energy of the x-ray photon is equal to the difference between the binding energy of the respective shells. Since atomic binding energies are unique to each element, the energy of the x-ray characteristic for that element.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Module 2: Interactions of Ionizing Radiation with Matter

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Describe how charged particles interact with matter and the resulting effects these interactions can have on the material.
2. Describe the processes by which x-ray and γ -ray photons interact with individual atoms in a material and the characteristics that determine which processes are likely to occur.
3. Identify how photons and charged particles are attenuated within a material and the terms used to characterize the attenuation.

Clinical Applications and Problem-Solving:

1. Identify which photon interactions are dominant for each imaging modality.
2. Understand how image quality and patient dose are affected by these interactions.
3. Understand which x-ray beam energies are to be used with intravenous iodine and oral barium contrast agents.
4. Understand how the types of photon interactions change with energy and their associated clinical significance.
5. Understand why charged particle interactions may result in a high localized dose.
6. Explain the purpose of adding filtration in x-ray imaging (e.g., copper, aluminum).
7. Understand how half-value layer affects patient dose.
8. Describe what makes a contrast agent radio-opaque.
9. Understand the effect of backscatter on skin dose.

Curriculum:

2. Interactions of Ionizing Radiation with Matter [3.0]
 - 2.1. Charged Particle Interactions [2.7]
 - 2.1.1. Ionization and Secondary Ionization [2.9]
 - 2.1.1.1. Specific Ionization [1.6]
 - 2.1.1.2. Linear Energy Transfer (LET) [2.7]
 - 2.1.1.3. Range [2.4]
 - 2.1.2. Excitation [2.1]
 - 2.1.3. Bremsstrahlung [3.0]
 - 2.1.4. Positron Annihilation [3.0]
 - 2.2. Photon Interactions
 - 2.2.1. Coherent Scattering [1.4]
 - 2.2.2. Photoelectric Effect [3.0]
 - 2.2.3. Compton Scattering [3.0]
 - 2.3. Photon Attenuation [3.0]
 - 2.3.1. Linear and Mass Attenuation [3.0]
 - 2.3.2. Mono-energetic and Poly-energetic Photon Spectra [3.0]
 - 2.3.3. Half-value Layer (HVL) [3.0]
 - 2.3.3.1. Effective Energy [2.7]
 - 2.3.3.2. Beam Hardening [2.7]

- 2.3.4. Interactions in Materials of Clinical Interest [2.9]
 - 2.3.4.1. Tissues [3.0]
 - 2.3.4.2. Radiographic Contrast Agents [3.0]
 - 2.3.4.3. Detectors [2.1]
 - 2.3.4.4. Shielding materials [2.3]

Example Q&A:

Q1. What is the predominant interaction of 120 kV x-rays from a computed tomography scanner with soft tissue?

- A. Coherent scattering
- B. Compton scattering
- C. Photoelectric effect
- D. Pair production

Answer: B – Compton scattering

Explanation: Above 25 keV, Compton scatter is the dominant photon interaction in soft tissue. Because CT x-ray beams have higher filtration than radiographic units, the effective energy is closer to one-half of the kV (60 keV).

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q2. If a radiologic technologist uses 80 kV for the AP projection of the lumbar spine, which of the following interactions will be the predominant interaction with *bone*?

- A. Coherent scattering
- B. Compton scattering
- C. Photoelectric effect
- D. Pair production

Answer: C – Photoelectric effect

Explanation: The average energy for an 80 kV spectrum is typically 1/3 to 1/2 of the maximal energy. X-ray photons in this range interact primarily by photoelectric interaction with bone. The primary interaction in this range (25–40 keV) with *soft tissue* is Compton scattering.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q3. During imaging of a patient, the proportion of Compton scatter is increased by increasing which of the following technical parameters?

- A. Exposure time
- B. Focal spot size
- C. kV
- D. Source-to-image receptor distance

Answer: C – kV

Explanation: The proportion of Compton scattering compared to photoelectric interactions increases with an increase in x-ray beam energy (kV, filtration).

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q4. Which of the following interactions is primarily responsible for patient dose in the low diagnostic energy range?

- A. Coherent scattering
- B. Compton scattering
- C. Photoelectric effect
- D. Pair production

Answer: C – Photoelectric effect

Explanation: Absorbed dose is energy absorbed per unit mass. In photoelectric effect, the incoming photon is completely absorbed locally.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q5. The predominant interaction of Tc-99m photons with a sodium iodide crystal is:

- A. Coherent scattering
- B. Compton scattering
- C. Photoelectric effect
- D. Pair production

Answer: C – Photoelectric effect

Explanation: Tc-99m gamma photons have energy of 140 keV. At this energy more than 50% of the interactions are photoelectric. (See Figure 3–11 in the Bushberg reference below.)

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q6. The unit for linear energy transfer (LET) is:

- A. keV per μm
- B. keV per density
- C. keV per mg
- D. keV per g

Answer: A – keV per μm

Explanation: Linear energy transfer is the average amount of energy deposited locally per unit path length. Do not confuse the units of LET with the units of absorbed dose, which is energy absorbed per mass. Increases in LET increase the radiation weighting factor.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q7. In interactions of x-ray and gamma ray radiation with matter, the occurrence of a sharp increase in photoelectric absorption is related to:

- A. density increases
- B. density decreases
- C. the photon energy being just above the atomic number of the substance
- D. the photon energy being just above the electron binding energy

Answer: D – the photon energy being just above the electron binding energy.

Explanation: Photoelectric absorption is proportional to Z^3/E^3 , and there is a sharp increase in absorption when the incoming photon energy is slightly above the electron binding energy.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q8. At 80 kV, assume the soft-tissue HVL is 4 cm. What is the approximate radiation dose to an embryo located 8 cm below the anterior surface, expressed as a percentage of the entrance skin dose?

- A. 100%
- B. 75%
- C. 50%
- D. 25%
- E. 12.5%

Answer: D – 25%

Explanation: At 80 kV, the half-value layer for soft tissue is approximately 3 to 4 cm. If the HVL is 3 cm of soft tissue, the embryo radiation dose would be 12.5% of the entrance skin dose. If the HVL is 4 cm of soft tissue, the radiation dose would be 25% of the entrance skin dose.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q9. Which of the following is the most penetrating of the radiations listed?

- A. Electrons from I-131 radioactive decay
- B. Photons from Tc-99m radioactive decay
- C. Positrons from F-18 radioactive decay
- D. Photons from F-18 radioactive decay

Answer: D – Photons from F-18 radioactive decay

Explanation: Penetration increases with energy, and the annihilation radiation at 511 keV is the most penetrating. When comparing between charged particulate radiation and photons of same energy, photons are more penetrating.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q10. The energy of each photon created when a positron interacts with an electron in an annihilation reaction is:

- A. 5 eV
- B. 140 keV
- C. 511 keV
- D. 1.022 MeV
- E. 3 MeV

Answer: C – 511 keV

Explanation: The rest mass of the electron and positron are each 511 keV for a total of 1.022 MeV. When the annihilation reaction occurs, two 511 keV photons are created.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q11. Which of the following is most damaging to tissue?

- A. Electrons (100 keV)
- B. Photons (diagnostic energy)
- C. Neutrinos
- D. Protons (100 keV)

Answer: D – Protons (100 keV)

Explanation: Neutrinos are near massless particles that undergo almost no interactions with any matter (many penetrate Earth without interacting). Photons undergo exponential attenuation, meaning the photon interactions are spread over all depths (some photons will not interact at all). When interactions do occur, either all (photoelectric effect), part (Compton scattering), or no (Rayleigh scattering) energy may be deposited locally. Electrons have a finite range, depositing energy locally by hard and soft collisions. Some energy will be lost due to radiative losses; further, the damage will be spread over the range of the electron. Protons lose little energy due to radiative losses, and the majority of the energy is deposited in a small volume close to the end of their range due to the presence of a Bragg peak.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Module 3: Radiation Units

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Recognize that there are two different systems for units of measurement (i.e., SI and traditional) used to describe physical quantities.
2. Describe the SI and traditional units for measuring the ionization resulting from radiation interactions in air (e.g., exposure-related quantities).
3. Describe the concepts of dose-related quantities and their SI and traditional units.

Clinical Applications and Clinical Problem-Solving:

1. Discuss the appropriate use or applicability of radiation quantities in the health care applications of imaging, therapy, and safety.
2. Identify appropriate units for a given dose metric.
4. Convert between dosages in MBq and dosages in mCi.
5. Understand when it is appropriate to use effective dose vs. absorbed dose.

Curriculum:

3. Radiation Units
 - 3.1. System of Units [3.0]
 - 3.1.1. SI [3.0]
 - 3.1.1.1. Prefixes: Nano- to Tera- [3.0]
 - 3.1.2. Traditional [2.8]
 - 3.2. Radioactivity [3.0]
 - 3.2.1. Dosage [3.0]
 - 3.2.2. SI – Becquerel (Bq) [3.0]
 - 3.2.3. Traditional – Curie (Ci) [3.0]
 - 3.3. Exposure [2.8]
 - 3.3.1. Coulomb/kilogram [2.0]
 - 3.3.2. Roentgen (R) [2.8]
 - 3.4. Kinetic Energy Released in Matter (KERMA) [2.8]
 - 3.4.1. Gray (Gy) [3.0]
 - 3.5. Absorbed Dose [3.0]
 - 3.5.1. Gray (Gy) [3.0]
 - 3.5.2. Rad [2.0]
 - 3.6. Equivalent Dose [3.0]
 - 3.6.1. Radiation Weighting Factors [2.8]
 - 3.6.2. Sievert (Sv) [3.0]
 - 3.6.3. Rem [2.5]
 - 3.7. Effective Dose [3.0]
 - 3.7.1. Tissue Weighting Factors [3.0]
 - 3.7.2. Sievert (Sv) [3.0]
 - 3.7.3. Rem [2.0]

Example Q&A:

Q1. The unit for effective dose is:

- A. R/min
- B. mGy
- C. mR
- D. mSv

Answer: D – mSv

Explanation: None

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q2. The absorbed dose multiplied by a weighting factor appropriate for the type of radiation is:

- A. Integral absorbed dose
- B. Equivalent dose
- C. Effective dose
- D. Committed equivalent dose

Answer: B – Equivalent dose

Explanation: By definition. Note that “equivalent dose”—obtained by multiplying the absorbed dose by the radiation weighting factor (W_R), which is a function of the type and energy of the radiation—is the definition to be used as given by the International Commission on Radiological Protection.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q3. A medical worker receives 30 mGy to an area of skin on the hand from alpha particles. The equivalent dose to this area of skin is:

- A. 30 mGy
- B. 30 mSv
- C. 600 mGy
- D. 600 mSv

Answer: D – 600 mSv

Explanation: Equivalent dose (H) = radiation weighting factor (W_R) times absorbed dose (D) where $W_R = 20$ for alpha particles. Equivalent dose is given in Sv.

References:

- 1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
- 2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q4. Match the following quantities with their SI units. Units may be used more than once.

- | | | |
|--------------------|-------|-------------------------|
| A. Absorbed dose | _____ | 1. Sievert |
| B. Equivalent dose | _____ | 2. Gray |
| C. Effective dose | _____ | 3. Roentgen |
| D. Air Kerma | _____ | 4. Coulomb per kilogram |
| E. Exposure | _____ | |

Answer: A.2, B.1, C.1, D.2, E.4

References:

- 1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
- 2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q5. Which quantity provides a single index that relates to the overall stochastic risk (at diagnostic radiation dose levels) when multiple organs are irradiated?

- A. Absorbed dose
- B. Equivalent dose
- C. Effective dose
- D. Air kerma
- E. Exposure

Answer: C – Effective dose

Explanation: Absorbed dose and equivalent dose are used to assess radiation risks to *individual* organs and tissues. Air kerma and exposure are both used to quantify the radiation intensity in air, but they do not provide an overall radiation risk index from multiple tissue and organ irradiation.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q6. Which statement is true regarding effective dose?

- A. It is dependent on co-morbidities.
- B. It is restricted only to single individual organ or tissue doses.
- C. It is a weighted sum of equivalent doses over multiple organs and tissues.
- D. It is independent of radiation type.

Answer: C – It is a weighted sum of equivalent doses over multiple organs and tissues.

Explanation: A is incorrect as the tissue weighting factors, W_T , used in the definition of effective dose (E) are for an average patients and do not consider co-morbidities. B is incorrect as effective dose can be used for both multiple- and single-organ and tissue irradiation. D is incorrect as equivalent dose includes the radiation weighting factors, W_R .

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q7. Convert a dosage of 20mCi Tc-99m to MBq of Tc-99m

- A. 0.54 MBq
- B. 20 MBq
- C. 37 MBq
- D. 740 MBq

Answer: D – 740 MBq

Explanation: 1 mCi is equal to 37 MBq.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Module 4: X-Ray Production

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Describe the two mechanisms by which energetic electrons produce x-rays and the energy distribution for each mechanism of x-ray production.
2. Describe the function of the cathode and anode of an x-ray tube and how variations in their design influence x-ray production.
3. Define technique factors used in diagnostic imaging, such as kV, mA, exposure time, and mAs.
4. Define the attributes of an x-ray beam, including the functions of filtration, spectrum of energies produced, and beam restriction.
5. Describe the heel effect and how it affects clinical radiographs.

Clinical Application and Problem-Solving:

1. Demonstrate how the x-ray tube design, target material, tube voltage, beam filtration, and focal spot size are optimized for a specific imaging task (e.g., mammography, interventional imaging, or CT).
2. How do kV, mAs, filtration, and field size impact x-ray intensity and beam quality?

Curriculum:

4. X-ray Production
 - 4.1. Bremsstrahlung [3.0]
 - 4.2. Characteristic Radiation [2.5]
 - 4.3. Production of X-rays [3.0]
 - 4.3.1. X-ray Intensity and Dose [3.0]
 - 4.3.2. Electron Energy [2.5]
 - 4.3.3. Target Material [3.0]
 - 4.3.4. Filtration [3.0]
 - 4.3.5. Spectrum and Beam Quality [3.0]
 - 4.4. X-ray Tube [3.0]
 - 4.4.1. Cathode [3.0]
 - 4.4.1.1. Filament [3.0]
 - 4.4.1.2. Focusing Cup [1.5]
 - 4.4.1.3. Filament Current and Tube Current [2.8]
 - 4.4.2. Anode [3.0]
 - 4.4.2.1. Composition [3.0]
 - 4.4.2.2. Configurations (e.g., Angulation, Stationary vs. Rotating) [1.8]
 - 4.4.2.3. Line-focus Principle [2.8]
 - 4.4.2.4. Focal Spot [3.0]
 - 4.4.2.5. Heel Effect [2.8]
 - 4.4.2.6. Off-focus Radiation [1.5]
 - 4.4.2.7. Tube Heating and Cooling [1.8]
 - 4.4.3. Applications [3.0]
 - 4.4.3.1. Mammography [3.0]
 - 4.4.3.2. Radiography and Fluoroscopy (R&F) [3.0]
 - 4.4.3.3. CT [3.0]

- 4.4.3.4. Interventional Fluoroscopy [3.0]
- 4.4.3.5. Mobile X-ray [3.0]
- 4.4.3.6. Dental [2.0]
- 4.5. Generators [2.0]
 - 4.5.1. High-frequency [2.0]
- 4.6. Technique Factors [3.0]
 - 4.6.1. Tube Voltage (kV) [3.0]
 - 4.6.2. Tube Current (mA) [3.0]
 - 4.6.3. Exposure Time [3.0]
 - 4.6.4. Automatic Exposure Control (AEC) [3.0]
 - 4.6.5. Technique Charts [2.8]
- 4.7. X-ray Beam Modification [3.0]
 - 4.7.1. Beam Filtration [3.0]
 - 4.7.1.1. Inherent [3.0]
 - 4.7.1.2. Added (Al, Cu, Mo, Rh, Ag, other) [3.0]
 - 4.7.1.3. Minimum HVL [3.0]
 - 4.7.1.4. Shaped Filters [1.5]
 - 4.7.2. Collimators [3.0]
 - 4.7.2.1. Field Size Limitation [1.0]
 - 4.7.2.2. Light Field and X-ray Field Alignment [1.0]
 - 4.7.2.3. Influence on Image Quality and Dose [3.0]
 - 4.7.2.4. Beam Shaping in IR [2.7]

Example Q&A:

Q1. What is a direct result of adding filtration to a diagnostic x-ray beam?

- A. All characteristic radiation is removed.
- B. Image contrast is improved.
- C. Maximum photon energy is increased.
- D. X-ray tube heat loading is reduced.
- E. Patient dose is reduced.

Answer: E – Patient dose is reduced.

Explanation: Added filters reduce the quantity of low-energy x-ray photons and “harden” the x-ray beam. Usually this is desirable because the removal of “soft” x-ray photons reduces patient skin dose.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q2. Which of the following always increases as focal spot size increases?

- A. Field of view
- B. Patient dose
- C. Geometric un-sharpness
- D. Anode diameter

Answer: C – Geometric un-sharpness

Explanation: The larger the focal spot size, the greater the geometric un-sharpness when combined with magnification. Larger focal spot size un-sharpness is not observable in contact radiography.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q3. In projection radiography, which of the following will reduce patient skin dose?

- A. Increased filtration
- B. Higher grid ratio
- C. Lower kV
- D. Smaller focal spot size

Answer: A – Increased filtration

Explanation: Added filters reduce the quantity of low-energy x-ray photons and “harden” the x-ray beam. Usually this is desirable because the removal of “soft” x-ray photons reduces the patient skin dose.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q4. With which of the following is the heel effect more pronounced?

- A. Image receptor farther from the focal spot
- B. Large focal spot size
- C. Smaller image size
- D. No grid
- E. X-ray tube with a smaller anode angle

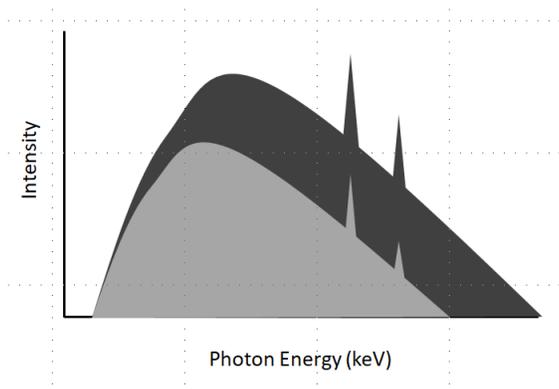
Answer: E – X-ray tube with a smaller anode angle.

Explanation: The x-ray intensity decreases from the cathode to the anode side of the beam. This variation in intensity across an x-ray beam is termed the heel effect. The heel effect is more pronounced when the anode angle is small and the SID is reduced.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*. 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q5. In the figure below, two x-ray tube spectra are compared. What single parameter was changed between the acquisitions of the spectra?



(Image courtesy William F. Sensakovic, PhD)

- A. kV
- B. Filtration
- C. Target material
- D. mAs

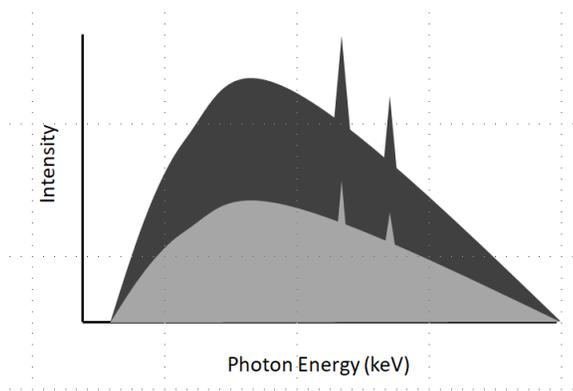
Answer: A – kV

Explanation: The low-energy end of each spectrum terminates at the same energy. This indicates that the filtration is the same for each spectrum. Each spectrum has the same characteristic x-ray peaks. This indicates that the target material is the same for each spectrum. If mAs was the only parameter that had been changed, the peak photon energy would be the same for the spectra. The maximum energy between the spectra has changed, which only occurs with a change in kV.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q6. In the figure below, two x-ray tube spectra are compared. What single parameter was changed between the acquisitions of the spectra?



(Image courtesy William F. Sensakovic, PhD)

- A. kV
- B. Filtration
- C. Target material
- D. mAs

Answer: D – mAs

Explanation: The low-energy end of each spectrum terminates at the same energy. This indicates that the filtration is the same for each spectrum. Each spectrum has the same characteristic x-ray peaks. This indicates that the target material is the same for each spectrum. Maximum energy did not change, so a change in kV did not occur. The only change in the spectrum is a change in x-ray quantity, which indicates a change in mAs.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2010.

Module 5: General Imaging and Informatics Concepts

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Define common descriptive statistics (e.g., mean, variance, etc.) used in the radiology literature.
2. Define the metrics and methods used to measure image quality and assess imaging systems.
3. Define the characteristics of a display and how they interact with the human visual system to impact perceived image quality.
4. Understand basic concepts of image processing and image archiving.

Clinical Application and Problem-Solving

1. Assess the validity of the type of statistical analysis used in the radiology literature.
2. Evaluate how display, ambient lighting, and luminance affect reader performance.
3. Develop custom hanging protocols for display of images.
4. Understand display quality control.
5. Understand the DICOM standard.
6. Know how to set up a quality improvement study.
7. Use ROC analysis to compare system performance.
8. Use window and level to improve lesion detectability.
9. Explain why high-resolution monitors are necessary for mammography.
10. Describe the pros and cons of a tablet vs. a diagnostic workstation.

Curriculum:

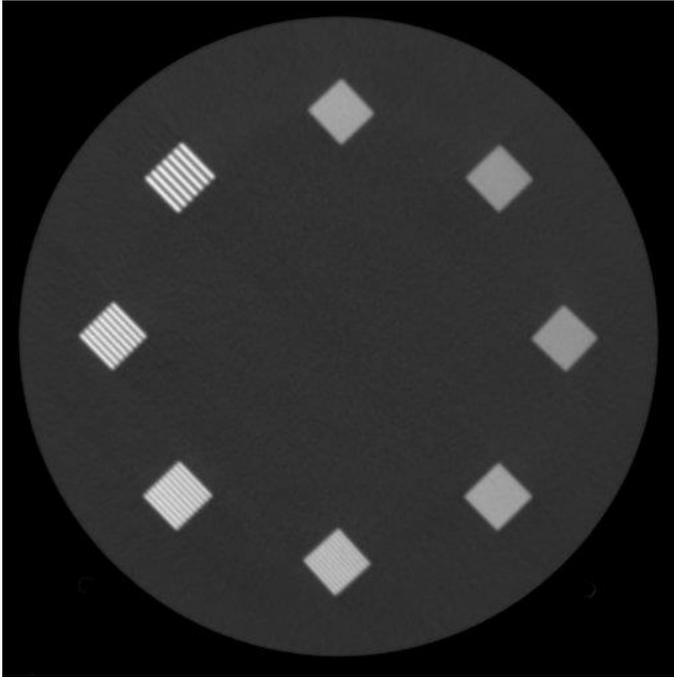
5. General Imaging and Informatics Concepts
 - 5.1. Introductory Statistics [3.0]
 - 5.1.1. Systematic and Random Error [3.0]
 - 5.1.2. Precision, Accuracy, and Reproducibility [3.0]
 - 5.1.3. Statistical Distributions: Poisson and Normal [2.7]
 - 5.1.4. Central Tendency: Mean, Median, and Mode [2.8]
 - 5.1.5. Dispersion: Standard Deviation, Variance, Range, and Percentiles [2.8]
 - 5.1.6. Correlation: Pearson Correlation [2.0]
 - 5.1.7. Confidence Intervals and Standard Error [1.8]
 - 5.1.8. Propagation of Error (Addition and Subtraction) [2.2]
 - 5.2. Basic Hypothesis Testing and Regression [1.3]
 - 5.3. Imaging System Properties and Image Quality Metrics [2.5]
 - 5.3.1. Image Domains [3.0]
 - 5.3.1.1. Spatial [3.0]
 - 5.3.1.2. Frequency [3.0]
 - 5.3.1.3. Temporal [3.0]
 - 5.3.2. Contrast (Physical vs. Image vs. Display) [3.0]
 - 5.3.3. Spatial Resolution [3.0]
 - 5.3.3.1. Point and Line Spread Functions [2.2]
 - 5.3.3.2. Full Width at Half Maximum (FWHM) [3.0]
 - 5.3.3.3. Modulation Transfer Function (MTF) [2.7]
 - 5.3.4. Noise [3.0]
 - 5.3.4.1. Quantum Mottle [3.0]

- 5.3.4.2. Other Sources [2.2]
- 5.3.4.3. Noise Frequency [1.7]
- 5.3.5. Dynamic Range and Latitude [2.8]
- 5.3.6. Contrast-to-Noise Ratio (CNR), Signal-to-Noise Ratio (SNR), Detective Quantum Efficiency (DQE) [2.8]
- 5.3.7. Temporal Resolution [3.0]
- 5.4. Image Representations [2.8]
 - 5.4.1. Pixels, Bytes, Field-of-View, and the Image Matrix [3.0]
 - 5.4.2. Grayscale and Color Images [3.0]
 - 5.4.3. Spatial Frequency and Frequency Space [3.0]
 - 5.4.3.1. Aliasing: Temporal, Spatial, and Bit-Depth [3.0]
 - 5.4.3.2. Nyquist Limit [2.8]
 - 5.4.4. Axial, Multi-planar, and Curvilinear Reconstructions [2.5]
 - 5.4.5. Maximum and Minimum Intensity Projections [2.5]
 - 5.4.6. Surface and Volume Rendering [2.0]
 - 5.4.7. Multi-Modal Imaging [2.3]
 - 5.4.8. Time-Resolved Imaging [2.7]
 - 5.4.9. Quantitative Imaging and Representation of Physical Data [2.5]
 - 5.4.9.1. Overlays, Color Maps, and Vectors [2.2]
- 5.5. Image Processing [3.0]
 - 5.5.1. Non-Uniformity and Defect Correction [2.8]
 - 5.5.2. Image Subtraction and Noise [3.0]
 - 5.5.3. Segmentation and the Region-of-Interest [3.0]
 - 5.5.3.1. Automated vs. Semi-automated vs. Manual [1.2]
 - 5.5.4. Look-up Tables (LUT) [2.7]
 - 5.5.4.1. Window and Level [3.0]
 - 5.5.4.2. Nonlinear Tables and Characteristic Curves [1.7]
 - 5.5.4.3. Histogram and Equalization [2.5]
 - 5.5.4.3.1. Value of Interest [2.2]
 - 5.5.4.3.2. Anatomical [2.2]
 - 5.5.5. Frequency Processing [2.3]
 - 5.5.5.1. Edge Enhancement [2.5]
 - 5.5.5.1.1. Un-sharp Masking [2.7]
 - 5.5.5.2. Smoothing [2.7]
 - 5.5.6. Digital Magnification (Zoom) [2.7]
 - 5.5.7. Quantitative Analysis [2.8]
 - 5.5.7.1. Object Size Measurement [2.7]
 - 5.5.7.2. Shape and Texture [1.5]
 - 5.5.7.3. Motion and Flow [1.3]
 - 5.5.8. Reconstruction [2.5]
 - 5.5.8.1. Simple Back-Projection [1.5]
 - 5.5.8.2. Filtered Back-Projection [2.5]
 - 5.5.8.3. Iterative Reconstruction Methods [2.8]
 - 5.5.8.4. Sinogram [2.3]
 - 5.5.9. Computer-Aided Detection and Diagnosis, Machine Learning, and Deep Learning (Artificial Intelligence) [2.3]
- 5.6. Display Characteristics and Viewing Conditions [3.0]
 - 5.6.1. Technologies [2.2]

- 5.6.1.1. Grayscale and Color [2.7]
- 5.6.2. Characteristics [2.7]
 - 5.6.2.1. Luminance [3.0]
 - 5.6.2.2. Pixel Pitch and Matrix Size [2.8]
 - 5.6.2.3. Quality Control [2.5]
 - 5.6.2.3.1. Grayscale Standard Display Function and Just Noticeable Differences [2.8]
- 5.6.3. Viewing Conditions [2.5]
 - 5.6.3.1. Viewing Distance [2.5]
 - 5.6.3.2. Viewing Angle [2.5]
 - 5.6.3.3. Ambient Lighting and Illuminance [2.5]
- 5.7. The Human Visual System, Perception, and Observer Studies [2.3]
 - 5.7.1. Visual Acuity, Contrast Sensitivity, and Conspicuity [2.3]
 - 5.7.2. Metrics of Observer Performance [1.8]
 - 5.7.2.1. Predictive Values [2.2]
 - 5.7.2.2. Sensitivity, Specificity, and Accuracy [2.7]
 - 5.7.2.3. Contrast-Detail [2.8]
 - 5.7.2.4. Receiver Operating Characteristic (ROC) Analysis [2.8]
- 5.8. Informatics [3.0]
 - 5.8.1. Basic Computer Terminology [2.8]
 - 5.8.2. Importance of Standards and Conformance [2.2]
 - 5.8.3. Integrating Healthcare Enterprise (IHE), Health Level 7 (HL7), and DICOM [2.7]
 - 5.8.3.1. Modality Work List [1.8]
 - 5.8.3.2. Components and Terminology of DICOM [2.8]
 - 5.8.4. Picture Archiving and Communication System (PACS), Radiology Information System (RIS), and Hospital Information System (HIS) [2.7]
 - 5.8.5. Electronic Medical Record (EMR) [2.3]
 - 5.8.6. Networks and Data (Image) Exchange [2.2]
 - 5.8.6.1. Bandwidth and Communication Concepts [1.5]
 - 5.8.7. Storage [2.3]
 - 5.8.7.1. Storage Requirements and Disaster Recovery [2.0]
 - 5.8.7.2. Lossy vs. Lossless Data Compression [2.7]
 - 5.8.8. Security and Privacy [2.0]
 - 5.8.8.1. Anonymization, Encryption, and Firewalls [1.8]
 - 5.8.8.2. Research, Health Insurance Portability and Accountability Act (HIPAA), and Institutional Review Boards (IRB) [2.3]

Example Q&A:

Q1. The image of the CT phantom is used to measure which image property?



(Image courtesy William F. Sensakovic, PhD)

- A. Spatial resolution
- B. Noise
- C. Dose
- D. Temporal resolution

Answer: A – Spatial resolution

Explanation: High-contrast spatial resolution or bar phantoms are composed of alternating opaque and translucent bars at increasing spatial frequencies. When imaged, the observer records the highest-frequency set of bars that can be resolved as the limiting spatial resolution of the system.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2010.
3. American College of Radiology. *ACR Computed Tomography Quality Control Manual*, 2012.

Q2. What metric evaluates the spatial resolution of an imaging system with change in spatial frequency?

- A. Modulation transfer function
- B. Point spread function
- C. Noise frequency
- D. Signal-to-noise ratio

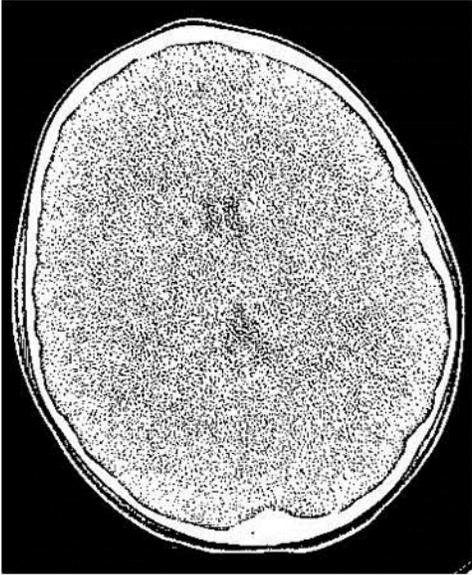
Answer: A – Modulation transfer function

Explanation: The modulation transfer function (MTF) is a measure of spatial resolution that describes the percentage of output signal contrast from an imaging system to the signal contrast input into the system as a function of spatial frequency. Due to various sources of blur in the imaging chain, the output signal contrast is always reduced compared to the input signal contrast. As spatial frequency, which is inversely related to object size, increases, MTF decreases. The limiting resolution of an imaging system is often given as the spatial frequency at which the MTF reaches 10%.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2010.

Q3. The CT image shown below is viewed at a window width of 2 HU and level of 2 HU. What single change below could be made to make the image more suitable for diagnostic viewing?



(Image Courtesy William F. Sensakovic, PhD)

- A. Increase window width
- B. Decrease window width
- C. Increase window level
- D. Decrease window level

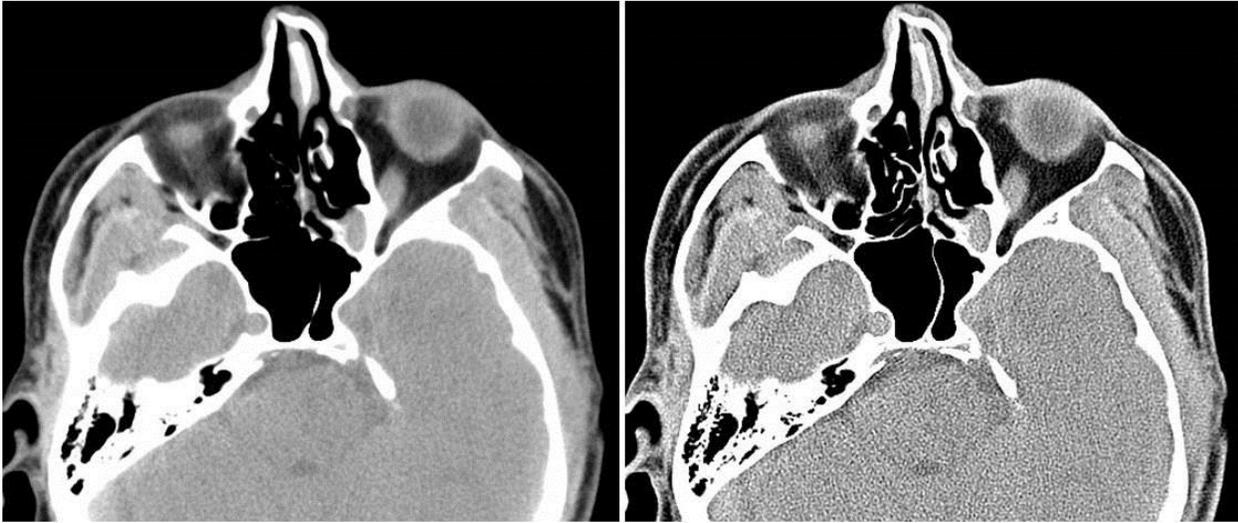
Answer: A – Increase window width

Explanation: Soft tissue is 0–100 HU, air –1000 HU, and bone 500 HU–1500 HU. Currently the image is viewed with the level at 2 HU, which is suitable for brain viewing and a window width of 2 HU (i.e., 1 HU below and 1 HU above the 2 HU center) which is not suitable for brain viewing. With this setting, it maps black to any pixel with a value less than 1 HU and white to any pixel with a value greater than 3 HU. This is a poor window because some soft tissue will have the same pixel intensity as bone (bright white). Similarly, some soft tissue and fat tissue will have the same pixel intensity as air (black). Finally, variations within soft-tissue will be lost. Increasing the window width will improve the contrast of different soft tissues in the image.

References:

1. Huda, W. *Review of Radiologic Physics*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2010.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q4. Which of the following is increased in the image on the right?



(Image Courtesy William F. Sensakovic, PhD)

- A. Noise
- B. Dose
- C. Contrast
- D. Blur

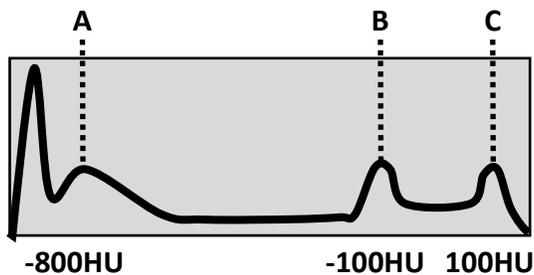
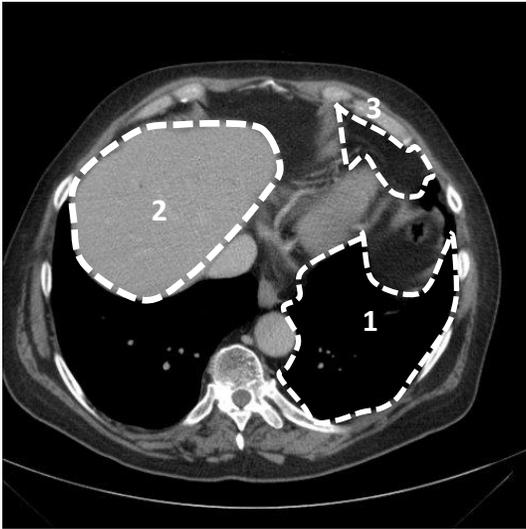
Answer: A – Noise

Explanation: The grainier appearance indicates that the noise is increased in the image on the right.

References:

1. Huda, W. *Review of Radiologic Physics*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2010.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q5. Match the outlined regions to their corresponding peaks on the histogram.



(Image Courtesy William F. Sensakovic, PhD)

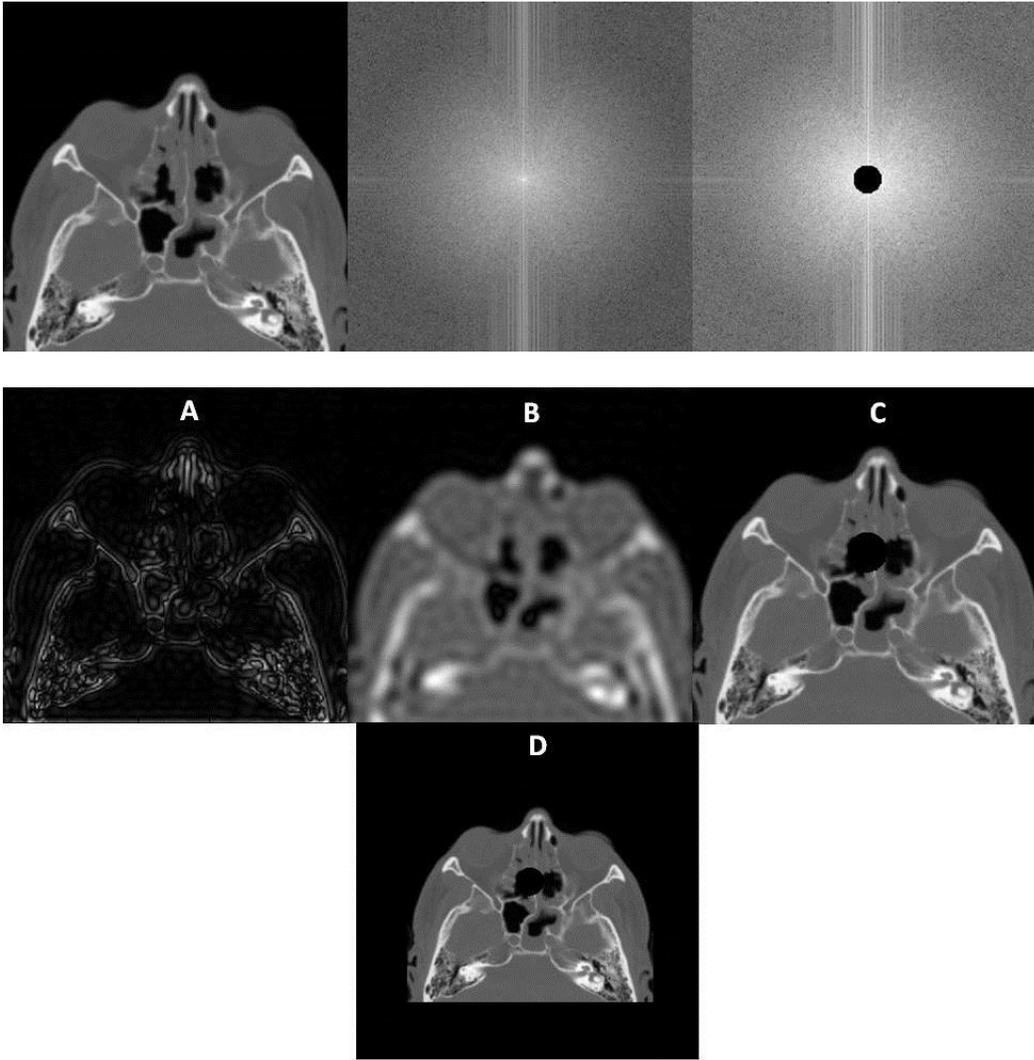
Answer: 1. A
2. C
3. B

Explanation: The histogram is the number of pixels of a given HU value vs. that value. Pixel values increase from low value on the left (black) to high value on the right (white). 1. Air and Lung (HU < -700). 2. Contrast-enhanced liver (HU ~80). 3. Visceral fat (HU ~ -100).

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Pisano, E.D., E.B. Cole, B.M. Hemminger, et al. "Image processing algorithms for digital mammography: a pictorial essay." *RadioGraphics* 20:1479-1491, 2000.

Q6. Given the original image (top left) and its Fourier Transform (top middle), which of the four images with letters below corresponds to altering the Fourier Transform as demonstrated in the top-right figure



(Image courtesy William F. Sensakovic, PhD)

- A.
- B.
- C.
- D.

Answer: A

Explanation: Image “A” illustrates the application of a high-pass filter, which discards all low spatial frequencies in the Fourier Spectrum. Thus only edges (high frequencies) are left in the image. Image “B” is the result of low-pass filtering in which high spatial frequencies are discarded, which blurs the image. Image “C” has simply had the value of all image pixels in the center of the image set to 0 (black color). Image “D” is image 3 reduced in size.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q7. The definition of segmentation in medical image processing is:

- A. Reduction of pixel intensity variations by averaging adjacent pixels
- B. Identification of the pixels that compose a structure of interest in an image
- C. Eliminating low spatial frequencies from the image
- D. Altering the relative intensities of the image pixels

Answer: B – Identification of the pixels that compose a structure of interest in an image.

Explanation: A is the definition of blurring or low-pass filtering, C is high-pass filtering or edge detection, and D is windowing or altering the look-up table. Segmentation is the identification of those pixels in the image that compose a structure or structures of interest to the observer or system.

References:

1. Bankman, I., ed. *Handbook of Medical Image Processing and Analysis*, 2nd ed. Burlington, MA: Academic Press, 2009.
2. Bick, U., M.L. Giger, R.A. Schmidt, et al. “Automated segmentation of digitized mammograms.” *Acad. Radiol.* 2:1–9, 1995.
3. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012

Q8. Detection of a large, low-contrast object in a noisy image can be improved by:

- A. Applying edge enhancement
- B. Applying image smoothing
- C. Increasing window width
- D. Digitally magnifying the image

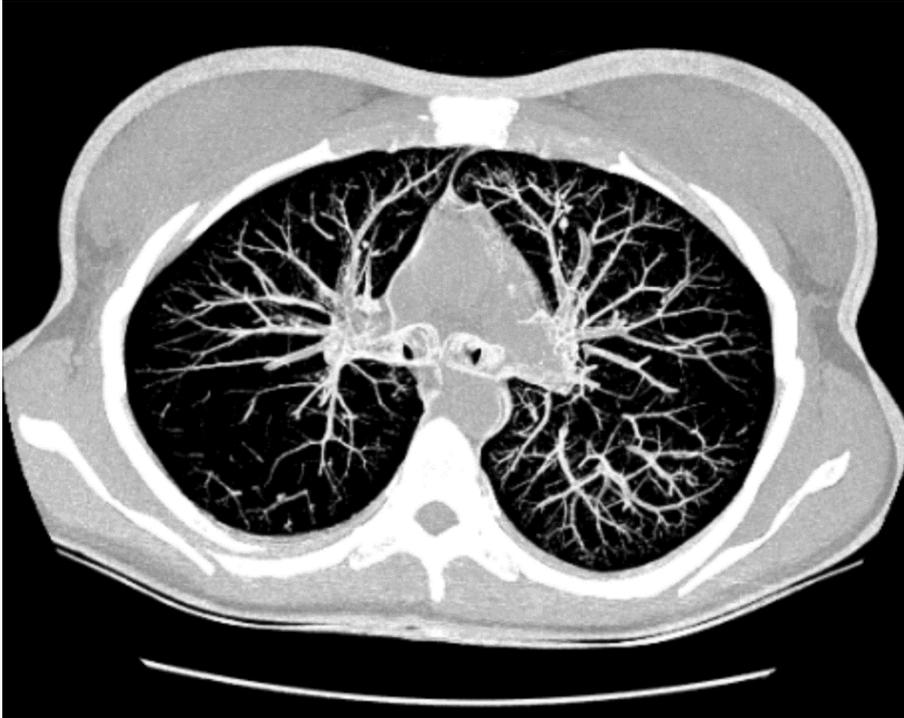
Answer: B – Applying image smoothing

Explanation: Edge enhancement will increase noise and will likely make detection more difficult. Applying smoothing reduces noise without reducing contrast (since the object is large) thus improving detectability. Increasing window width will decrease the apparent noise, but it also decreases display contrast, making detection more difficult. Digitally magnifying the object forces the eye to concentrate on the noise instead of the already large object, making detection more difficult. Often it is better to reduce zoom (magnification), which increases averaging of pixels in the eye and effectively smooths the image.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Sprawls, P. “Image Characteristics and Quality” at <http://www.sprawls.org/ppmi2/IMGCHAR/#Compromises>. Accessed 04/27/2015.

Q9. What type of CT image is shown below?



(Image courtesy William F. Sensakovic, PhD)

- A. MIP
- B. Surface render
- C. Volume render
- D. MPR
- E. Fused image

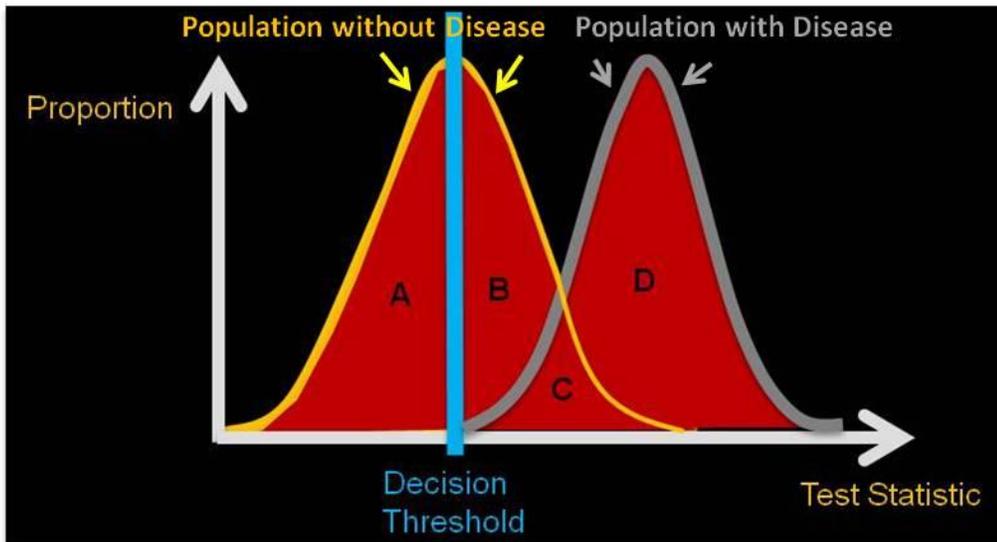
Answer: A – MIP

Explanation: A maximum-intensity projection looks at several CT sections and displays the brightest value for each pixel. This is why several layers of rib and entire lung vessels can be visualized on one section. A surface-rendered image shows a 3D rendering of one or several organ surfaces. A volume render shows a semitransparent 3D rendering of one or more organs. Both surface and volume renderings are usually color images to aid in visualization. Fused images are the combination of more than one image, usually from different modalities (e.g., PET and CT). A multi-planar reconstruction involves reconstructing the information in a different plane (usually coronal).

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Beigelman-Aubry, C., C. Hill, A. Guibal, et al. “Multi-detector row CT and postprocessing techniques in the assessment of diffuse lung disease.” *Radiographics* 25:1639–1652, 2005.

Q10. You are evaluating a new diagnostic test. All patients with test statistic above the decision threshold are diagnosed disease positive by the test. Match the following regions:



(Image courtesy William F. Sensakovic, PhD)

- 1) Regions C & D
- 2) Region A
- 3) Regions B & C

- I. True Negative
- II. True Positive
- III. False Positive

Answer: I. True Positive – 1) Regions C & D
 II. True Negative – 2) Region A
 III. False Positive – 3) Regions B & C

Explanation: Region A contains only true negative results. Region B contains only false positive results. Region C contains both false positive (under yellow curve) and true positive (under gray curve) results. Region D contains only true positive results.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2010.

Module 6: Biological Effects of Ionizing Radiation

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Describe the various factors that impact cell radiosensitivity.
2. Define the principles of how radiation deposits energy that can cause biological effects and impact cell survival.
3. Explain the difference between direct and indirect effects, how radiation affects DNA, and how radiation damage can be repaired.
4. Compare the radiosensitivities of different organs in the body.
5. Know the thresholds for deterministic effects.
6. Discuss the risk of stochastic effects due to radiation.
7. Describe the effect of radiation on mutagenesis and teratogenesis.
8. List the most probable *in utero* radiation effects and their thresholds at different stages of gestation.
9. Describe the different dose response models for radiation effects.

Clinical Application and Problem-solving:

1. Understand the risks to patients from high-dose fluoroscopy regarding deterministic effects and the importance of applying radiation protection principles in clinical protocols to avoid damage.
2. Understand the risks to the female breast (including age dependence).
3. Counsel a pregnant woman on the potential radiation risks to the fetus.
4. Recognize the benefit vs. risk in radiation uses, and recognize the information sources that can be used to assist in assessing this ratio.

Curriculum:

6. Radiation Biology
 - 6.1. Principles
 - 6.1.1. Linear Energy Transfer (LET) [2.0]
 - 6.1.2. Relative Biological Effectiveness (RBE) [2.3]
 - 6.1.2.1. Radiation Weighting Factors [3.0]
 - 6.1.3. Tissue Weighting Factors [3.0]
 - 6.2. Molecular Effects of Radiation [2.7]
 - 6.2.1. Direct vs. Indirect Effects [2.7]
 - 6.2.2. Effects of Radiation on DNA [2.3]
 - 6.3. Cellular Effects of Radiation [2.3]
 - 6.3.1. Law of Bergonié and Tribondeau [2.7]
 - 6.3.2. Radiosensitivity of Different Cell Types [2.7]
 - 6.3.3. Cell Cycle Radiosensitivity [1.7]
 - 6.3.4. Cell Damage, Survival, Repair, and Death [2.3]
 - 6.4. Systemic Effects of Radiation [2.7]
 - 6.4.1. Tissue and Organs [2.7]
 - 6.4.2. Whole Body [3.0]
 - 6.4.3. Population (Age and Gender) [3.0]
 - 6.5. Tissue Reactions (Deterministic) Effects [3.0]
 - 6.5.1. Acute Radiation Syndromes [2.3]

- 6.5.1.1. Sequence of Events [2.0]
- 6.5.1.2. Hematopoietic [2.3]
- 6.5.1.3. Gastrointestinal [2.3]
- 6.5.1.4. Neurovascular [2.3]
- 6.5.1.5. LD50/60 [2.3]
- 6.5.1.6. Monitoring and Intervention [2.3]
- 6.5.2. Skin Effects [3.0]
- 6.5.3. Lens Effects [3.0]
- 6.5.4. Reproductive Impact [2.7]
- 6.6. Stochastic Radiation Effects [3.0]
 - 6.6.1. Radiation Epidemiological Studies [2.3]
 - 6.6.2. Carcinogenesis [2.7]
 - 6.6.2.1. Radiation-Induced Cancers [3.0]
 - 6.6.2.1.1. Leukemia [3.0]
 - 6.6.2.1.2. Solid Tumors [3.0]
 - 6.6.2.2. Spontaneous Rate (Natural Incidence) [3.0]
 - 6.6.2.3. Latency [3.0]
 - 6.6.3. Mutagenesis [2.3]
- 6.7. Teratogenesis [2.7]
 - 6.7.1.1. Developmental Effects [3.0]
 - 6.7.1.2. Childhood Leukemia [2.7]
 - 6.7.1.3. Gestational Sensitivity [2.7]
- 6.8. Radiation Risk [3.0]
 - 6.8.1. Benefit vs. Risk in Radiology [3.0]
 - 6.8.2. Definition and Communication of Risk (e.g., relative, absolute, etc.) [2.3]
 - 6.8.3. Dose-Response Models [3.0]
 - 6.8.3.1. Linear, No-Threshold (LNT) [3.0]
 - 6.8.3.2. Linear-Quadratic [2.7]
 - 6.8.3.3. Radiation Hormesis/Adaptive Response [2.0]
 - 6.8.3.4. Bystander Effect [2.3]
- 6.9. Information Sources [2.3]
 - 6.9.1.1. Biological Effects of Ionizing Radiation Reports (e.g., BEIR VII) [2.3]
 - 6.9.1.2. International Council on Radiation Protection (ICRP) [2.3]
 - 6.9.1.3. National Council on Radiation Protection (e.g., NCRP 116, 168) [2.3]
 - 6.9.1.4. United Nations Scientific Committee on the Effects of Atomic Radiation Reports (UNSCEAR) [2.3]
 - 6.9.1.5. Nuclear Regulatory Commission (NRC) [2.3]
 - 6.9.1.6. National Cancer Institute (NCI) Common Toxicity Criteria for Dermatology/Skin [2.3]
 - 6.9.1.7. American College of Radiology (ACR) Appropriateness Criteria for Medical Procedures [2.7]

References:

1. Hall, E. and Giaccia, A.J. *Radiobiology for the Radiologist*, 8th ed. Wolters Kluwer, 2019.
2. NCRP Report No. 160, Ionizing Radiation Exposure of the Population of the United States.
3. Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2 (2006).
4. UNSCEAR 2013 report Vol. II Sources, Effects and Risks of Ionizing Radiation (2013)
 - a. Annex B: Effects of radiation exposure of children (2 MB)

Example Q&A:

Q1. Which of the following has the highest LET?

- A. Alpha particle
- B. Gamma ray
- C. X-ray
- D. Beta particle

Answer: A – Alpha particle

Explanation: Linear energy transfer, or LET, refers to the amount of energy deposited locally in tissue per unit path length. Alpha particles have high LET due to their relatively large mass and higher charge.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Hall, E.J. and A.M. Giaccia. *Radiobiology for the Radiologist*, 7th ed. Philadelphia: Lippincott William & Wilkins, 2011.

Q2. In which phase of the reproductive cycle are cells most sensitive to the damaging effects of radiation?

- A. G1 phase
- B. S phase
- C. G2 phase
- D. M phase

Answer: D – M phase

Explanation: Cells are generally most sensitive to radiation damage when they are in mitosis. Mitosis is the most sensitive phase because of lack of checkpoint prior to DNA duplication and fewer resistive mechanisms available as compared to the other phases of reproduction. DNA is also exposed during the mitotic process, making it more exposed as a target.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Hall, E.J. and A.M. Giaccia. *Radiobiology for the Radiologist*, 6th ed. Philadelphia: Lippincott William & Wilkins, 2006.

Q3. Most radiation-induced injury is due to damage to which type of molecules?

- A. Deoxyribonucleic acid
- B. Ribonucleic acid
- C. DNA polymerase
- D. Hemoglobin

Answer: A – Deoxyribonucleic acid

Explanation: There is strong evidence that the biologic effects of radiation damage—including cell killing, carcinogenesis, and mutation—result from double stranded breaks (DSB) in the double helical structure of DNA.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Hall, E.J. and A.M. Giaccia. *Radiobiology for the Radiologist*, 7th ed. Philadelphia: Lippincott William & Wilkins, 2011.

Q4. Which of the following is a stochastic effect of radiation?

- A. Hair loss
- B. Skin erythema
- C. Cataract
- D. Carcinogenesis

Answer: D – Carcinogenesis

Explanation: Risk is calculated as a stochastic or statistical probability, so increased risk of cancer is a non-deterministic (stochastic) effect. All other effects are tissue (deterministic) effects.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Hall, E.J. and A.M. Giaccia. *Radiobiology for the Radiologist*, 7th ed. Philadelphia: Lippincott William & Wilkins, 2011.

Q5. What is the LD_{50/60} for humans?

- A. 1 gray
- B. 2 gray
- C. 3 gray
- D. 4 gray

Answer: A – 4 gray

Explanation: The LD_{50/60} for humans is 4 Gy. Lethal dose 50/60 is the dose of radiation to the whole body that causes 50% of irradiated subjects to die within 60 days without medical intervention.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Hall, E.J. and A.M. Giaccia. *Radiobiology for the Radiologist*, 7th ed. Philadelphia: Lippincott William & Wilkins, 2011.

Q6. What is a potential risk to the fetus from a pelvic CT exam acquired during the 30th week of gestation?

- A. Fetal malformation
- B. Prenatal death
- C. Childhood cancer
- D. Cataracts

Answer: C – Childhood cancer

Explanation: The risk to the fetus from low levels of radiation (below 50 mGy) is negligible. At 30 weeks of pregnancy the woman is well into the third trimester, and during this stage of gestation, the only potential risk is from a stochastic effect, which is childhood cancer. The dose from an abdomen/pelvic CT scan is well below the thresholds necessary to cause deterministic effects in earlier stages of pregnancy.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Hall, E.J. and A.M. Giaccia. *Radiobiology for the Radiologist*, 7th ed. Philadelphia: Lippincott William & Wilkins, 2011.

Q7. What is the most radiosensitive organ in young women?

- A. Breast
- B. Brain
- C. Gonads
- D. Skin

Answer: A – Breast

Explanation: Of the tissues listed, breast tissue is among the most radiosensitive organs. The tissue weighting factor is 0.12 for breast, 0.01 for brain, 0.08 for gonads, and 0.01 for skin. The tissue weighting factors are based on population averages between males and females over all ages. Radiosensitivity is higher for younger women.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Hall, E.J. and A.M. Giaccia. *Radiobiology for the Radiologist*, 7th ed. Philadelphia: Lippincott William & Wilkins, 2011.

Q8. What dose-response model does the BEIR VII report recommend for calculating the risk of solid tumor induction from ionizing radiation?

- A. Linear-quadratic
- B. Linear, threshold
- C. Linear, no-threshold
- D. Radiation hormesis

Answer: C – Linear, no-threshold

Explanation: Based on a review of epidemiological data, the BEIR VII report indicates the best model for solid tumor response is the linear, no-threshold dose response model. The linear-quadratic model is used for leukemia response.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. National Research Council of the National Academies. *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII, Phase 2*. Washington, D.C.: National Academies Press, 2006.

Q9. Match the radiation dose to the corresponding stage of acute radiation syndrome.

- | | |
|----------|------------------------------|
| A. 3 Gy | 1. Hematopoietic Syndrome |
| B. 12 Gy | 2. Neurovascular Syndrome |
| C. 50 Gy | 3. Gastrointestinal Syndrome |

Answer: A.1, B.3, C.2

Explanation: At 3 Gy, death from hematopoietic syndrome becomes a risk (in about one month). At 10 Gy, the patient still has hematopoietic syndrome, however, gastrointestinal syndrome is also present and is lethal in less time (about a week) than hematopoietic syndrome. Finally, at 50 Gy, a patient will have hematopoietic, gastrointestinal, and neurovascular (AKA, cerebrovascular (CNS)) syndromes.

References:

1. Hall, E.J. and Giaccia, A.J. *Radiobiology for the Radiologist*, 7th ed. Philadelphia: Lippincott Williams & Wilkins, 2011.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q10. What is the equivalent dose to a patient from 10 mGy of alpha particles?

- A. 0.5 mSv
- B. 10 mSv
- C. 50 mSv
- D. 200 mSv

Answer: D – 200 mSv

Explanation: The radiation weighting factor of alpha particles is 20, making them much more damaging than electrons or photons in the diagnostic energy range.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda W, et al. *Review of Radiological Physics*, 4th ed. Lippincott Williams & Wilkins, 2016.

Module 7: Radiation Protection and Associated Regulations

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Identify the sources of background radiation and the contribution from each source.
2. State the maximum permissible dose equivalent limits to the public and radiation workers.
3. Identify the advisory bodies, accrediting organizations, and regulatory organizations for radioactive materials and radiation-generating equipment, and recognize their respective roles.
4. Define the principles of time, distance, shielding, and contamination control in radiation protection.
5. Define ALARA and its application in radiation protection.
6. Identify the methods used to monitor occupational exposure.
7. Discuss appropriate equipment used to monitor radiation areas or contamination.

Clinical Applications and Problem-Solving:

1. Understand the safety considerations for patients and staff, including pregnant staff.
2. Use your knowledge of radiation effects to discuss how you would triage patients during a radiological emergency.
3. Discuss the contributions of medical sources to the collective effective dose.
4. Define the responsibilities and qualifications of an authorized user (all categories) and a radiation safety officer.
5. Explain how radiation protection equipment is utilized in the clinical environment.
6. Understand the importance of applying radiation protection principles in clinical protocols.
7. Understand the best use of gonad shielding and breast shields for patients.
8. Describe the requirements for wipe tests and contamination surveys.
9. Provide clinical examples that demonstrate ALARA principles.
10. Discuss the appropriate written instructions provided to breast-feeding patients receiving a nuclear medicine study.
11. Describe the factors that affect dose to a pregnant person seated next to a patient injected with a radionuclide for a diagnostic or therapeutic procedure.
12. Describe the steps used in applying procedure appropriateness criteria.
13. Describe the release criteria for patients administered a radioactive material.
14. Describe how a medical event is defined and the appropriate response to an identified medical event.

Curriculum:

7. Radiation Protection and Associated Regulations
 - 7.1. National Council on Radiation Protection (NCRP) 160 [3.0]
 - 7.1.1. Natural Background [3.0]
 - 7.1.2. Medical Dose to Patients [3.0]
 - 7.1.3. Consumer Products and Activities [1.0]
 - 7.1.4. Industrial, Security, Medical, Educational, and Research [1.0]
 - 7.1.5. Occupational [2.3]
 - 7.2. Medical Sources: Occupational Doses [3.0]
 - 7.2.1. Projection Radiography [2.7]

- 7.2.2. Mammography [2.7]
- 7.2.3. Fluoroscopy [3.0]
- 7.2.4. Interventional Radiology and Diagnostic Angiography [3.0]
- 7.2.5. CT [3.0]
- 7.2.6. Sealed Source Radioactive Material [2.7]
- 7.2.7. Unsealed Source Radioactive Material [2.7]
- 7.3. Monitoring Patient Dose [3.0]
 - 7.3.1. Diagnostic Reference Levels (DRL) and “Trigger” Levels [3.0]
 - 7.3.2. Joint Commission Sentinel Events [3.0]
 - 7.3.3. Nuclear Regulatory Commission (NRC) Medical Event [3.0]
 - 7.3.4. Patient Dose Tracking [3.0]
- 7.4. Dose limits [3.0]
 - 7.4.1. Occupational Dose Limits [3.0]
 - 7.4.1.1. Effective Dose [3.0]
 - 7.4.1.2. Specific Organ [2.3]
 - 7.4.1.3. Pregnant Workers [3.0]
 - 7.4.1.4. Limit to Minors [1.0]
 - 7.4.2. Members of the Public [3.0]
 - 7.4.2.1. General [3.0]
 - 7.4.2.2. Caregivers [2.7]
- 7.5. Radiation Detectors [3.0]
 - 7.5.1. Personnel Dosimeters [3.0]
 - 7.5.1.1. Thermoluminescent Dosimeters (TLDs) [2.3]
 - 7.5.1.2. Optically Stimulated Luminescent (OSL) Dosimeters [3.0]
 - 7.5.1.3. Direct-Ion Storage Dosimeters [1.0]
 - 7.5.1.4. Real-Time Dosimeters 1.3]
 - 7.5.1.5. Applications: Appropriate Use and Wearing [3.0]
 - 7.5.1.6. Limitations and Challenges in Use [2.3]
 - 7.5.2. Area Monitors [2.0]
 - 7.5.2.1. Dosimeters [1.7]
 - 7.5.2.2. Ion Chambers [3.0]
 - 7.5.2.3. Geiger–Müller (GM) [3.0]
 - 7.5.2.4. Scintillators [3.0]
- 7.6. Principles of Radiation Protection [3.0]
 - 7.6.1. Time [3.0]
 - 7.6.2. Distance [3.0]
 - 7.6.3. Shielding (Personal) [3.0]
 - 7.6.4. Shielding (Structural) [1.0]
 - 7.6.4.1. Uncontrolled vs. Controlled [1.7]
 - 7.6.5. Contamination Control [3.0]
 - 7.6.6. As Low as Reasonably Achievable (ALARA) [3.0]
 - 7.6.7. Procedure Appropriateness (Justification) [2.7]
- 7.7. Advisory Bodies [1.7]
 - 7.7.1. International Commission on Radiological Protection (ICRP) [1.7]
 - 7.7.2. National Council on Radiation Protection and Measurements (NCRP) [1.7]
 - 7.7.3. Conference of Radiation Control Program Directors (CRCPD) [1.3]
 - 7.7.4. International Atomic Energy Agency (IAEA) [1.3]
 - 7.7.5. American College of Radiology (ACR) [2.0]

- 7.7.6. National Electrical Manufacturers Association (NEMA) (Medical Imaging and Technology Alliance or MITA) [1.7]
- 7.7.7. International Commission on Radiation Units [1.3]
- 7.8. Regulatory Agencies [2.3]
 - 7.8.1. U.S. Nuclear Regulatory Commission and Agreement States [2.3]
 - 7.8.1.1. 10 CFR Parts 19, 20, 30, 32, 35, 110 [2.3]
 - 7.8.1.2. The Joint Commission (TJC) [2.3]
 - 7.8.1.3. Guidance Documents (NUREG 1556, Vols. 9 & 11) [1.7]
 - 7.8.1.4. Regulatory Guides [1.0]
 - 7.8.2. States: For Machine-Produced Sources [1.0]
 - 7.8.2.1. Suggested State Regulations [1.0]
 - 7.8.3. U.S. Food and Drug Administration (FDA) [1.7]
 - 7.8.4. U.S. Office of Human Research Protections (OHRP) [1.3]
 - 7.8.5. U.S. Department of Transportation (DOT) [2.0]
 - 7.8.6. U.S. Department of Labor (OSHA) [1.0]
 - 7.8.7. International Electro-Technical Commission (IEC) [1.3]
- 7.9. Radiation Safety with Radioactive Materials [3.0]
 - 7.9.1. Surveys [3.0]
 - 7.9.1.1. Area [3.0]
 - 7.9.1.2. Wipe Test [3.0]
 - 7.9.1.3. Spills [3.0]
 - 7.9.2. Ordering, Receiving, and Unpacking Radioactive Materials [3.0]
 - 7.9.3. Contamination Control [3.0]
 - 7.9.4. Radioactive Waste Management [3.0]
 - 7.9.5. Qualifications for Using Radioactive Materials
 - 7.9.5.1. Diagnostic Authorized User (10 CFR 35.200 and 35.100, or Equivalent Agreement State Regulations) [3.0]
 - 7.9.5.2. Therapeutic Authorized User (10 CFR 35.300 and 35.1000, or Equivalent Agreement State Regulations) [3.0]
 - 7.9.5.3. Radiation Safety Officer [3.0]
 - 7.9.6. Medical Events [3.0]
 - 7.9.6.1. Reportable [2.3]
 - 7.9.6.2. Person or Agency to Receive Report [1.7]
 - 7.9.7. Special Considerations [1.3]
 - 7.9.7.1. Pregnant Patients [2.7]
 - 7.9.7.2. Breast-Feeding Patients [2.7]
 - 7.9.7.3. Caregivers [2.7]
 - 7.9.7.4. Patient Release [2.7]
 - 7.9.7.5. Written Instructions [2.7]
- 7.10. Estimating Effective Fetal Dose (Procedure-Specific Doses) [2.7]
 - 7.10.1. Radiography [2.0]
 - 7.10.2. Mammography [2.0]
 - 7.10.3. Fluoroscopy [2.0]
 - 7.10.4. Computed Tomography [2.7]
 - 7.10.5. Nuclear Medicine [2.7]
- 7.11. Radiological Emergencies [1.7]
 - 7.11.1. Triage: Evaluation, Dispensation, and Initial Treatment [1.7]

Example Q&A:

Q1. What is the yearly effective dose limit for radiologists under current regulations?

- A. 10 mSv
- B. 50 mSv
- C. 100 mSv
- D. 0.5 mSv
- E. 1.0 mSv

Answer: B – 50 mSv

Explanation: The annual effective dose limit for occupational workers is 50 mSv.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q2. By what factor has the yearly natural background radiation received per capita changed over time (NCRP Reports 93 (1987) and 160 (2006))?

- A. Increased by a factor of two
- B. Increased by a factor of four
- C. Increased by a factor of six
- D. Stayed the same
- E. Decreased

Answer: D – Stayed the same

Explanation: Background effective dose has approximately stayed the same over time at about 3 mSv per year.

References:

1. National Council on Radiation Protection & Measurements. *NCRP Report 93 – Ionizing Radiation Exposure of the Population of United States*. Bethesda, MD: NCRP, 1987.
2. National Council on Radiation Protection & Measurements. *NCRP Report 160 – Ionizing Radiation Exposure of the Population of the United States*. Bethesda, MD: NCRP, 2009.

Q3. What percentage of average yearly effective dose to the U.S. population is from medical sources?

- A. 10%
- B. 25%
- C. 50%
- D. 75%
- E. 90%

Answer: C – 50%

Explanation: The total contribution from medical sources is approximately 3.0 mSv per capita per year in NCRP Report 160 (2009), a six-fold increase from 0.5 mSv per year. The total from all sources is approximately 6.2 mSv.

References:

1. National Council on Radiation Protection & Measurements. *NCRP Report 160 – Ionizing Radiation Exposure of the Population of the United States*. Bethesda, MD: NCRP, 2009.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q4. Which of the following organizations is an advisory body?

- A. U.S. Nuclear Regulatory Commission (NRC)
- B. Food and Drug Administration (FDA)
- C. National Council on Radiation Protection and Measurement (NCRP)
- D. U.S. Department of Transportation (DOT)

Answer: C – National Council on Radiation Protection and Measurement (NCRP)

Explanation:

Regulatory Agencies:

- U.S. Nuclear Regulatory Commission (NRC) regulates special nuclear material, source material, by-product material of nuclear fission, and the maximum permissible dose equivalent limits.
 - 10 CFR Parts 20 (standards for protection against radiation)
 - 10 CFR Parts 19, 30, 32, 35, 110
- Food and Drug Administration (FDA) regulates radiopharmaceutical development, manufacturing, performance, and radiation safety requirements associated with the production of commercial x-ray equipment and mammography.
- U.S. Department of Transportation (DOT) regulates the transportation of radioactive materials used in nuclear medicine and radiation oncology.

Advisory Bodies:

- National Council on Radiation Protection and Measurements (NCRP) collects, analyzes, develops, and disseminates information in the public interest. The NCRP makes non-regulatory recommendations about radiation protection, radiation measurements, quantities, and units.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, Chapter 21, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q5. As reported in NRC Report 160, which category contributes the highest percentage to the total annual dose per capita?

- A. Internal
- B. Radon
- C. Cosmic
- D. Medical

Answer: D – Medical

Explanation: Medical includes the sum of the computed tomography (1.5 mSv per year), interventional fluoroscopy, conventional rad/fluoro, and nuclear medicine (0.80 mSv per year) contributions to the total annual dose per capita. Medical contributes 3.0 mSv per year, whereas radon's contribution is about 2.3 mSv per year. Therefore, the medical category is the highest percentage of the total. Cosmic radiation only contributes roughly 0.34 mSv per year.

References:

1. National Council on Radiation Protection & Measurements. *NCRP Report 160 – Ionizing Radiation Exposure of the Population of the United States*. Bethesda, MD: NCRP, 2009.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, Chapter 21, 2012.

Q6. What type of radiation badge is typically worn by a radiologist?

- A. Block dosimeter
- B. Scintillation detector
- C. Geiger–Müller (GM) detector
- D. Optically stimulated luminescence (OSL) dosimeter

Answer: D – Optically stimulated luminescence (OSL) dosimeter

Explanation: Personnel monitors are usually film badges (an old method), OSLs (optically stimulated luminescence), or TLDs (thermoluminescent dosimeters, usually used for ring badges). The most common badge is an OSL.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, Chapter 21, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q7. What would be the first thing to do when a critically injured person, who may have been contaminated with radioactive material, enters the emergency department?

- A. Remove clothing and wrap in a sheet.
- B. Rinse the person with lukewarm water.
- C. Respond and treat the injury.
- D. Do blood work to determine the possible dose.

Answer: C – Respond and treat the injury.

Explanation: As given in the reference: “treatment of life or limb threatening medical conditions should take precedence over decontamination. Standard Precautions are generally adequate to provide protection for first responders, emergency medical personnel, and clinicians.”

References:

1. Center for Disease Control. *Population Monitoring in Radiation Emergencies: A Guide for State and Local Public Health Officials*, 2nd ed. Department of Health and Human Services, CDC, 2014, Section 3.0, p. 3 Guiding Principles.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, Chapter 21, 2012.

Q8. Which of the following constitutes a medical event?

- A. 5 mCi of Tc99m sulfur colloid to the wrong patient
- B. 0.3 mCi of I-131 NaI rather than 0.3 mCi I-123 NaI for uptake on a hyperthyroid patient
- C. 30 mCi rather than the standard 8 mCi of Tc99m sestamibi for a cardiac study
- D. 20 mCi of sestamibi (cardiac agent) rather than 20 mCi of MDP (bone agent) to the correct patient

Answer: B – 0.3 mCi of I-131 NaI rather than 0.3 mCi I-123 NaI for uptake on a hyperthyroid patient

Explanation: A medical event is defined as wrong patient, radionuclide, route of administration, or radiopharmaceutical, a greater than 20% difference between prescribed and administered dosage AND the effective dose equivalent exceeds 0.05 Sv or 0.5 Sv to an organ or tissue, or 0.5 Sv dose equivalent to the skin. The administration of diagnostic amounts of radioactive materials, other than I-131 sodium iodide (NaI), will not, in general, result in exceeding the dose thresholds.

Reference:

1. 10 CFR Part 35.3045. Definition of medical event.

Q9. Which of the following studies requires more than a 24 hour interruption in breastfeeding?

- A. 10 mCi F-18 FDG
- B. 4 mCi Tc 99m pertechnetate
- C. 20 mCi Rb 82 chloride
- D. 0.5 mCi In-111 white blood cells

Answer: D – 0.5 mCi In-111 white blood cells

Explanation: For all other choices, either the radioisotope physically decays away too quickly to result in significant dose to a breastfeeding infant after 24 hours or it is expelled from the mother's body through other routes and is not substantially expressed in the breast milk.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, Chapter 21, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q10. What would be the instrument of choice for determining the location of a Tc ^{99m} radioactive spill?

- A. NaI well counter
- B. Portable ionization chamber
- C. Geiger–Müller survey meter
- D. Radionuclide calibrator

Answer: C – Geiger–Müller survey meter

Explanation: A Geiger–Müller Survey Meter is the most sensitive handheld detector that can be used. This allows it to detect very low levels of contamination.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, Chapter 21, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q11. If a written directive is required for a procedure, the radiologist ordering the procedure must be approved for which category of use?

- A. 10 CFR 35.100
- B. 10 CFR 35.200
- C. 10 CFR 35.300
- D. 10 CFR 35.500

Answer: C – 10 CFR 35.300

Explanation: 10 CFR 35.300 Subpart E: Unsealed Byproduct Material–Written Directive Required. 35.100 is uptake applications, 35.200 is imaging and localization, and 35.500 is authorization for transmission sources such as Gadolinium 153.

Reference:

1. 10 CFR Part 35 Subpart E.

Q12. Which of the following may be held for decay in storage until background levels are obtained?

- A. Cobalt 57 marker source
- B. Cesium 137 reference source for well counter
- C. Gadolinium 153 transmission rod
- D. Iodine 125 seed for breast localization

Answer: D – Iodine 125 seed for breast localization

Explanation: I-125 has a half-life of 60 days. Decay in storage may be used for radioactive materials with a half-life of 120 days or less. All the others listed have a half-life greater than 120 days.

References:

1. 10 CFR Part 35.92.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q13. To authorize the release of a patient treated with a therapeutic dosage of radioactive material, the dose to the most likely exposed individual must be less than what value?

- A. 0.1 mSv
- B. 0.5 mSv
- C. 1 mSv
- D. 5 mSv

Answer: D – 5 mSv

Explanation: As given in 10 CFR Part 35.75, “the licensee may authorize release if...total effective dose to any other individual from exposure to the released individual is not likely to exceed 5 mSv.” If the exposure from the individual could result in total effective dose equivalent greater than 1 mSv, written instructions on minimizing exposure to others must also be given.

Reference:

1. 10 CFR Part 35.75

Q14. A patient has an endoleak, with imaging repeated multiple times in six months. The system-measured values for cumulative air kerma ($K_{a,r}$) are recorded each time and are 5 Gy, 5.5 Gy, 7 Gy, and 4.5 Gy. Which of the following agencies may require reporting of this?

- A. Nuclear Regulatory Commission
- B. Food and Drug Administration, Center for Devices and Radiological Health
- C. Joint Commission
- D. National Council on Radiation Protection and Measurements

Answer: C – Joint Commission.

Explanation: This may be a reviewable sentinel event, which is defined as prolonged fluoroscopy with peak skin dose >15 Gy over some period of time, which Joint Commission gives as six months to one year.

Reference:

1. http://www.jointcommission.org/assets/1/18/Radiation_Overdose.pdf

Module 8: General Radiography – Projection Imaging Concepts and Detectors

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Review the detector types used to acquire an x-ray images. Describe how radiation is detected by each detector type and the different attributes of each detector for recording information.
2. Describe the components of a radiographic imaging system.
3. List and describe the factors affecting radiographic image quality.
4. Explain how the geometric features of a general radiographic system affect the resulting image.
5. Distinguish among the basic imaging requirements for specific body parts or views acquired in general radiography.
6. Define entrance skin air kerma and how it relates to patient dose.
7. Define Exposure Index and Deviation Index.

Clinical Applications and Problem-Solving:

1. Describe how variations in system configuration affect the resultant image.
2. Describe how each detector type influences image quality and dose.
3. Develop appropriate technique factors used in common radiographic procedures.
4. Analyze the radiation dose from a medical procedure, and communicate the potential risks.
5. Determine when use of a grid is warranted or inappropriate.
6. Identify common artifacts seen in radiography and how they can be mitigated.
7. Discuss how the geometry of a projection imaging system affects patient dose and image quality.
8. Discuss the properties (size, detection efficiency, etc.) of a detector system that determine its suitability for pediatric procedures.

Curriculum:

8. General Radiography – Projection Imaging Concepts and Detectors
 - 8.1. Underlying Technology and Physics Principles
 - 8.1.1. Geometry [3.0]
 - 8.1.1.1. Inverse-Square Law [3.0]
 - 8.1.1.2. Beam Divergence and Radiation Field Size (Field of View) [3.0]
 - 8.1.1.3. System Geometry [3.0]
 - 8.1.1.3.1. Source-to-Image Distance (SID) [3.0]
 - 8.1.1.3.2. Source-to-Object Distance (SOD) [3.0]
 - 8.1.1.3.3. Object-to-Image Distance (OID) [3.0]
 - 8.1.1.3.4. Geometric Magnification [3.0]
 - 8.1.2. Primary System Components [3.0]
 - 8.1.2.1. X-ray Tube and Generator [3.0]
 - 8.1.2.2. Filtration (Inherent, Added, and Compensation) [2.8]
 - 8.1.2.3. Collimator Assembly (Collimator and Light Field) [2.8]
 - 8.1.2.4. Anti-Scatter Grid and Bucky [3.0]
 - 8.1.2.5. Automatic Exposure Control (AEC) [3.0]
 - 8.1.2.6. Detector [3.0]

- 8.1.2.7. Control Console [2.2]
- 8.1.3. Radiographic Detectors [3.0]
 - 8.1.3.1. Detector Characteristics [2.6]
 - 8.1.3.1.1. Dynamic Range [2.6]
 - 8.1.3.1.2. Quantum Mottle, Electronic Noise, and Saturation [2.4]
 - 8.1.3.1.3. Detection Efficiency (Sensitivity) [1.4]
 - 8.1.3.2. Computed Radiography (CR, PSP-Photostimulable Phosphor) [2.4]
 - 8.1.3.2.1. Primary Components – Imaging Plate and Plate Reader[2.4]
 - 8.1.3.2.2. Storage Phosphors and Latent Image Formation [2.2]
 - 8.1.3.2.3. Signal Readout and Image Formation [2.2]
 - 8.1.3.2.4. Pre-Processing (Gain, Uniformity Correction, etc.) [2.0]
 - 8.1.3.2.5. Post-Processing (Histogram Equalization, etc.) [2.0]
 - 8.1.3.3. Indirect and Direct Digital Detectors [3.0]
 - 8.1.3.3.1. Primary Components [3.0]
 - 8.1.3.3.2. Detector Element Size [3.0]
 - 8.1.3.3.3. Charge Conversion (Photon to Electrical Signal) [1.4]
 - 8.1.3.3.4. Charge Collection (Charge-Coupled Devices (CCD) and Thin-Film Transistors (TFT)) [1.0]
 - 8.1.3.3.5. Signal Readout and Image Formation [1.4]
 - 8.1.3.3.6. Pre-Processing (Gain, Bad Pixel Correction, etc.) [1.8]
 - 8.1.3.3.7. Post-Processing (Histogram Equalization, etc.) [1.6]
 - 8.1.3.4. Pediatric vs. Adult [2.2]
 - 8.1.3.5. Strengths and Weaknesses of Each Detector Type [3.0]
- 8.2. Effective Use
 - 8.2.1. Applications [3.0]
 - 8.2.1.1. Head/Neck [2.6]
 - 8.2.1.2. Chest [2.8]
 - 8.2.1.3. Abdomen/Pelvis [2.8]
 - 8.2.1.4. Spinal [2.6]
 - 8.2.1.5. Extremities [2.8]
 - 8.2.1.6. Adult/Pediatric/Neonatal [2.86]
 - 8.2.2. Acquisition Modes [3.0]
 - 8.2.2.1. Stationary vs. Portable [3.0]
 - 8.2.2.2. Table Bucky, Wall Stand, 'Free Cassette,' and Table Top [3.0]
 - 8.2.2.3. Manual vs. AEC Technique [3.0]
 - 8.2.3. Scatter and Scatter Reduction [3.0]
 - 8.2.3.1. Scatter-to-Primary Ratio (Patient Size, Field Size, Acquisition Technique) [3.0]
 - 8.2.3.2. Anti-Scatter Grid [3.0]
 - 8.2.4. System Setup and Patient Positioning [3.0]
 - 8.2.4.1. Collimation, Light Field, and Field of View [3.0]
 - 8.2.4.2. Positioning Effects on Dose and Image Quality [3.0]
 - 8.2.4.3. Anti-Scatter Grid [3.0]
 - 8.2.4.3.1. Grid Ratio [3.0]
 - 8.2.4.3.2. Focal Distance and SID [2.6]
 - 8.2.4.3.3. Appropriate Selection [2.8]

- 8.2.4.3.4. Bucky Factor [3.0]
- 8.2.5. Technique Selection [2.8]
- 8.3. Image Characteristics and Artifacts
 - 8.3.1. Image Quality Characteristics [3.0]
 - 8.3.1.1. Hi-Contrast Spatial Resolution [3.0]
 - 8.3.1.1.1. Focal Spot Size and Geometric Blur [3.0]
 - 8.3.1.1.2. Detector Blur [3.0]
 - 8.3.1.1.3. Magnification [3.0]
 - 8.3.1.2. Low-Contrast Resolution (LCR) and Contrast Sensitivity [2.2]
 - 8.3.1.2.1. Subject and Image Contrast [2.8]
 - 8.3.1.2.2. Collimation and Scatter [3.0]
 - 8.3.1.3. Image Noise and Signal-to-Noise Ratio (SNR) [3.0]
 - 8.3.1.3.1. Receptor Dose, Exposure Index (EI), and Deviation Index (DI) [2.4]
 - 8.3.1.3.2. Structured, Electronic, Anatomical, and Quantum Noise [2.2]
 - 8.3.1.4. Technique Selection Effect on Image Quality [2.8]
 - 8.3.1.5. Temporal Resolution – Exposure Time [2.4]
 - 8.3.1.6. Inherent Trade-Offs between Radiation Dose and Image Quality [2.8]
 - 8.3.2. Planar Radiography Artifacts and Image Degradation [2.8]
 - 8.3.2.1. Anatomical Superposition [3.0]
 - 8.3.2.2. Patient Motion [2.8]
 - 8.3.2.3. Anti-Scatter Grid – Alignment, Focal Distance, Grid Cutoff [2.8]
 - 8.3.2.4. Field Uniformity and the Heel Effect [2.8]
 - 8.3.2.5. Image Processing [2.4]
 - 8.3.3. Computed Radiography (CR) [2.2]
 - 8.3.3.1. Acquisition Artifacts (e.g., Double Exposure, Fogged Plate) [2.2]
 - 8.3.3.2. Hardware Artifacts (e.g., Debris, Mechanical Stress, Incomplete Erasure) [2.2]
 - 8.3.3.3. Software Artifacts (e.g., Radiation Field Identification and Processing) [2.0]
 - 8.3.4. Digital Radiography (DR) [2.6]
 - 8.3.4.1. Readout Errors (e.g., Power Interruption, Electromagnetic Interference) [2.4]
 - 8.3.4.2. Detector (e.g., Dead Pixels) [2.8]
 - 8.3.4.3. Processing (e.g., Uniformity Correction) [2.4]
- 8.4. Safety, Quality Management, and Regulatory Issues
 - 8.4.1. Factors Affecting Patient Dose [2.8]
 - 8.4.1.1. Patient Habitus [2.6]
 - 8.4.1.2. Patient Shielding [1.6]
 - 8.4.1.3. Appropriate Use of AEC [3.0]
 - 8.4.2. Radiation Dose and Dose Indicators [3.0]
 - 8.4.2.1. Entrance Skin Air Kerma [3.0]
 - 8.4.2.2. Kerma-Area Product (KAP) [2.4]
 - 8.4.2.3. Effective Dose [2.8]
 - 8.4.2.4. Exposure Index (EI)/Deviation Index (DI) [2.8]
 - 8.4.2.5. Dose Reference Levels [2.6]
 - 8.4.2.6. Typical Values (Adult, Pediatric, and Fetal) [3.0]

- 8.4.3. Quality Assurance and Quality Control Program [1.0]
 - 8.4.3.1. Repeat/Reject Analysis [1.4]
 - 8.4.3.2. EI/DI Analysis [1.4]
 - 8.4.3.3. State/Federal Regulatory Requirements [1.2]
 - 8.4.3.4. Oversight of Physicists and Technologists QA/QC Activities [1.3]

Example Q&A:

Q1. (Effective Use) What exam is typically performed **without** an anti-scatter grid?

- A. Lateral Hip
- B. Lateral lumbar spine
- C. AP wrist
- D. AP abdomen

Answer: C – AP wrist

Explanation: The purpose of the grid is to remove scatter radiation generated in the patient prior to absorption in the image receptor. The amount of scatter generated in the patient increases with increased kV, field size, and patient thickness. Of the exams listed, the AP wrist would involve the lowest kV, smallest field size, and thinnest anatomy, therefore generating the least amount of scatter radiation. Extremity radiographs are often taken on the table top with the extremity placed directly on the detector.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008.

Q2. (Image Quality and Artifacts) What acquisition parameter change will improve low contrast visibility?

- A. Decreasing tube voltage
- B. Increasing SID
- C. Increasing filtration
- D. Decreasing focal spot size

Answer: A – Decreasing tube voltage

Explanation: Decreasing tube voltage will increase photoelectric absorption, which will increase subject contrast. The other factors will not increase subject contrast.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008.

Q3. (Underlying Technology and Physics Principles) How would the effect of geometric blur on a radiographic image be minimized?

- A. Use the highest mA and shortest exposure time available.
- B. Use a small focal spot.
- C. Use the detector with the largest available pixel size.
- D. Use immobilization devices.

Answer: B – Use a small focal spot.

Explanation: Geometric blur, also called focal spot blur, increases with focal spot size and magnification.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008.

Q4. (Underlying Technology and Physics Principles) What is the actual size of an object located half way between the x-ray tube and the image receptor if the object measures 10 mm on the image?

- A. 1 mm
- B. 5 mm
- C. 15 mm
- D. 20 mm

Answer: B – 5 mm

Explanation: The factor by which an object is magnified in a radiographic image is determined by the ratio of the source-to-image distance (SID) to the source-to-object distance (SOD). If the SOD is half of the SID, then the magnification factor would be 2 and the object would appear twice as large in the image compared to its actual size.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008.

Q5. (Underlying Technology and Physics Principles) What is a definition of a Bucky Factor?

- A. Percent contrast improvement with a grid
- B. Relative increase in x-ray intensity when a grid is used
- C. Ratio of grid height to width
- D. Number of grid lines per centimeter

Answer: B – Relative increase in intensity when a grid is used

Explanation: The Bucky factor is the relative increase in x-ray intensity (or mAs) when a grid is used vs. when a grid is not used.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008.

Q6. (Underlying Technology and Physics Principles) What is the effect of reducing the SID from 72” to 40”?

- A. Radiation dose to the patient will decrease.
- B. Image spatial resolution will improve.
- C. Image noise will increase.
- D. The object of interest will appear larger on the image.

Answer: D – The object of interest will appear larger on the image.

Explanation: The factor by which an object is magnified in a radiographic image is determined by the ratio of the source-to-image distance (SID) to the source-to-object distance (SOD). Decreasing the SID also decreases the SOD, with a resulting increase in the ratio of SID over SOD, thereby increasing magnification.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008.

Q7. (Effective Use) What parameter change can be made to reduce scatter production in the patient?

- A. Change from a 10:1 to an 8:1 grid.
- B. Move the patient closer to the image receptor.
- C. Reduce tube current.
- D. Use a smaller field of view.

Answer: D – Use a smaller field of view.

Explanation: Using a smaller field of view results in less scatter production in the patient and less scatter reaching the image receptor.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008.

Q8. (Underlying Technology and Physics Principles) What type of detector system uses a storage phosphor to capture the x-ray signal?

- A. Indirect Digital Radiography
- B. Direct Digital Radiography
- C. Computed Radiography
- D. Film-screen Radiography

Answer: C – Computed Radiography

Explanation: The phosphor used in CR is barium fluorohalide. Electrons in the phosphor layer are excited by the absorption of x-rays into traps where they remain until released by the application of laser energy, which occurs in the CR reader.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008.

Q9. (Underlying Technology and Physics Principles) What system element affects spatial resolution in direct radiography flat panel detector systems?

- A. Phosphor thickness
- B. Detector element size
- C. Laser spot size
- D. Field of view

Answer: B – Detector element size

Explanation: The signal recorded in each detector element (dixel) is converted to a single shade of gray pixel value in the image. Smaller dexels result in better spatial resolution.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Dance, D.R. *Diagnostic Radiology Physics*. IAEA, 2014.

Q10. (Image Quality and Artifacts) What is responsible for the heart appearing enlarged on an AP chest image as compared to a PA chest image?

- A. The focal spot size
- B. The use of focused grids
- C. Greater scatter from objects closer to the x-ray tube
- D. The outward divergence of the x-ray beam from the focal spot

Answer: D – The outward divergence of the x-ray beam from the focal spot

Explanation: The projection of an object by diverging x-rays from a point source (focal spot) is magnified in the imaging plane by the factor SID/SOD, where SID is the focus-to-image detector distance and SOD is the focus-to-object distance. Since the heart is positioned anteriorly in the body, it is closer to the x-ray tube in the AP view. Therefore, the SOD is smaller, and the heart appears more magnified than in the PA view.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q11. (Effective Use) What is the reason for excluding high-ratio grid use for mobile radiography?

- A. High-ratio grids have poorer scatter rejection than low-ratio grids.
- B. High-ratio grids are more difficult to align with the focal spot.
- C. High-ratio grids are more easily mis-positioned upside down as compared with low-ratio grids.
- D. High-ratio grids cannot be manufactured with short enough focal lengths.

Answer: B – High-ratio grids are more difficult to align with the focal spot.

Explanation: High-ratio grids are more difficult to center under the x-ray tube focal spot than low-ratio grids due to the lack of an accurate alignment system on most portable x-ray units. This leads to mis-centering and, therefore, grid cutoff, which degrades image quality by lowering the SNR. This is why low-ratio grids are generally used for portable work.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q12. (Effective Use) A radiograph of a neonate airway was obtained in the 1.5X geometric magnification mode. What acquisition parameter is the most critical to ensure optimal spatial resolution?

- A. Added filtration
- B. High kV
- C. Small focal spot size
- D. Large SID
- E. High mAs

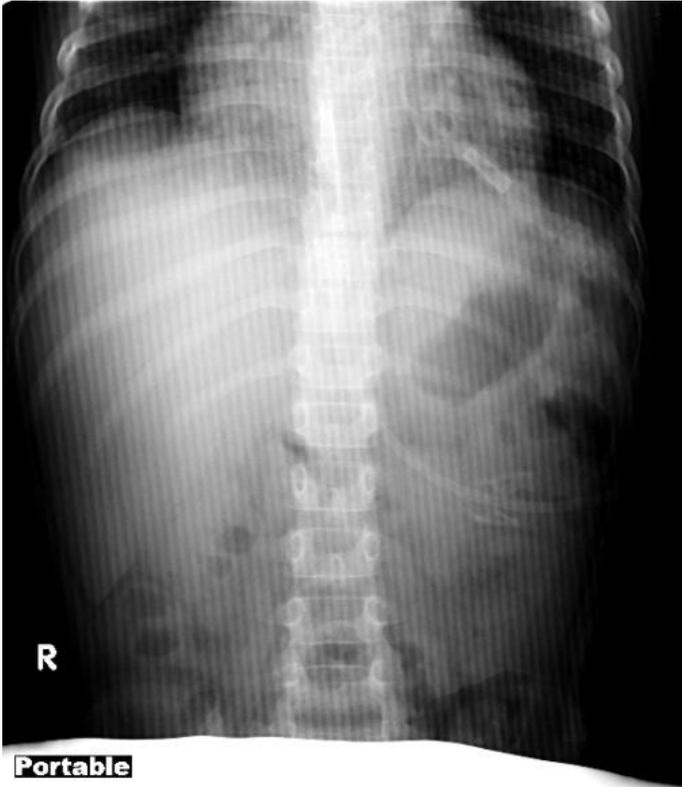
Answer: C – Small focal spot size

Explanation: Normally, the x-ray tube for radiography has dual focal spot sizes of 0.6 mm and 1.2 mm. However, for this kind of magnification mode, a 0.3 mm focal spot size is crucial to limiting focal spot blur and, therefore, helping ensure limited geometric unsharpness and optimal spatial resolution.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Nickoloff, E.L., et al. "Pediatric high kV/filtered airway radiographs: comparison of CR and film-screen systems." *Pediatr. Radiol*, 2002.

Q13. (Image Quality and Artifacts) Identify the artifact in the digital radiography image below.



(Image Credit: Jones AK, et al. Ongoing quality control in digital radiography: Report of AAPM Imaging Physics Committee Task Group 151. Appendix A. Med. Phys. 42 (11), 2015)

- A. Dead pixels
- B. Grid line interference
- C. Grid inserted upside down
- D. Patient motion

Answer: B – Grid line interference

Explanation: When the number of grid lines per cm (grid frequency) is comparable to the number of detector pixels per cm, an interference (or moiré) pattern such as this can be generated. This is most likely to occur for low-frequency stationary grids due to aliasing when the grid frequency just exceeds the pixel sampling rate.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q14. (Underlying Technology and Physics Principles) For a dedicated chest radiography room, the x-ray tube for the wall stand should be set with:

- A. The anode side up and the cathode side down
- B. The anode side down and the cathode side up
- C. Either anode up or down, it makes no difference in chest image quality
- D. Whether anode up or down depends on patient size
- E. Whether anode up or down depends on radiologist's preference

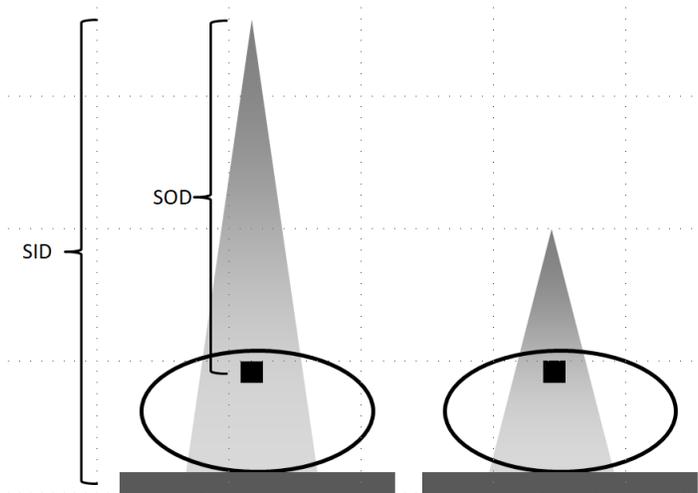
Answer: A – The anode side up and the cathode side down

Explanation: The x-ray intensity decreases from the cathode to the anode side of the beam. This variation in intensity across an x-ray beam is termed the heel effect. To compensate for the heel effect, a patient's thicker portion should be near the cathode side and the thinner portion should be near the anode side. In a dedicated chest radiographic room, the neck portion should be near the anode side and the diaphragm portion should be near the cathode side. For the wall stand, the x-ray tube should be oriented in the way that the anode side is up and the cathode side is down.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q15. (Image Quality and Artifacts) Under automatic exposure control (AEC), increasing the SID from 40" to 72" in radiography results in:



(Image courtesy William F. Sensakovic, PhD)

- A. Shorter exposure times
- B. Decreased focal spot blurring
- C. An increase in patient exposure
- D. Noisier images

Answer: B – Decreased focal spot blurring

Explanation: Focal spot blur decreases with decreasing geometric magnification ($M = \text{SID}/\text{SOD}$). Increasing the SID also increases the SOD by the same amount (32"), but since the SID is greater than the SOD, the SOD increases *proportionally* faster than the SID, leading to a decrease in the object's magnification M and, thus, decreased focal spot blur. For AEC operation, the exposure is the same to the image receptor at both SIDs, but the SOD is greater at the 72" SID. Thus, the patient entrance exposure will be lower. Using AEC, the dose to the image receptor is constant, irrespective of the SID, so image quantum noise remains the same. Since the image receptor is farther away, longer exposure times are needed to keep the image receptor dose constant (assuming the kV and mA are fixed).

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q16. (Safety, Quality Management, and Regulatory Issues) Match the x-ray procedure to the effective dose:

- | | |
|--------------------------------------|--------------|
| 1. Abdomen | A. 0.001 mSv |
| 2. Extremities | B. 0.7 mSv |
| 3. Two view mammogram (both breasts) | C. 0.02 mSv |
| 4. Posteroanterior chest | D. 0.01 mSv |
| 5. Shoulder | E. 0.4 mSv |

Answer: 1.B, 2.A, 3.E, 4.C, and 5.D

Explanation: Approximate average effective doses: extremities = 0.001 mSv, shoulder = 0.01 mSv, PA chest = 0.02 mSv, two view mammogram exam = 0.4 mSv, and abdomen = 0.7 mSv.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q17. (Underlying Technology and Physics Principles) How does the spatial resolution of an indirect conversion digital radiography system compare to a direct system?

- A. Better
- B. Equivalent
- C. Worse

Answer: C – Worse than a direct conversion digital radiography system

Explanation: The spread of light in the scintillator of an indirect conversion digital radiography system adds blurring to the image, which reduces resolution.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q18. (Safety, Quality Management, and Regulatory Issues) In taking an abdominal radiograph of a pregnant patient, what is the single most important thing that you can do to ensure the lowest dose to the fetus while acquiring the most appropriate image?

- A. Use a high kV
- B. Shield the fetus
- C. Reduce the FOV with collimation
- D. Position prone instead of supine
- E. Remove the anti-scatter grid

Answer: C – Reduce FOV with collimation

Explanation: High kVp leads to lower doses, but to decreased image contrast as well. Wrapping the patient in lead does not reduce the greatest source of radiation to the fetus, which is internal scatter from the mother. Although the lead does protect the fetus from x-ray tube leakage and scatter off the collimators, these are negligible compared with the internal scatter from nearby irradiated tissue. Scatter is directly proportional to the volume of tissue being irradiated. Collimating down to only three quarters of each of the original field dimensions results in a 44% reduction in irradiated area, and thus a 44% reduction in scatter. Collimate down to half the field dimensions and the scatter reduction is 75%. Reduction of scatter also improves the image contrast. Prone or supine makes little difference with regard to internal scatter to the fetus. Removing the grid will reduce the exposure to the mother, and hence the amount of internal scatter to the fetus, by factors of 1.5 to 2.5, depending upon the grid's Bucky factor. However, without the grid to help block much of the scatter to the image receptor, the image will be dominated by scatter and be considered unacceptable.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Wagner, L.K., R.G. Lester, and L.R. Saldana. *Exposure of the Pregnant Patient to Diagnostic Radiations: A Guide to Medical Management*, 2nd ed. Madison, WI: Medical Physics Publishing, 1997.

Q19. (Safety, Quality Management, and Regulatory Issues) For a KUB on an average-sized patient, what would be a reasonable technique to acquire the radiograph?

- A. 75 kV, 20 mAs, 40" SID
- B. 120 kV, 12 mAs, 40" SID
- C. 50 kV, 50 mAs, 72" SID
- D. 75 kV, 2.5 mAs, 72" SID

Answer: A – 75 kV, 20 mAs, 40" SID

Explanation: We know that patient dose decreases with increasing kV, but so does subject contrast. Further, very low mAs values lead to noisy images. Knowing this, we can eliminate answer B because 120 kV gives too low contrast. We can eliminate answer C because of the large SID and the higher dose from the 50 kV beam (but contrast would be high). Answer D can be eliminated because of the low mAs and large SID. Answer A is a reasonable compromise at 20 mAs, a typical SID, and a moderate kV.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Module 9: Mammography

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Discuss the clinical importance of breast imaging as a screening and diagnostic tool.
2. Identify breast imaging systems (including tomosynthesis and biopsy) and associated system components.
3. Describe the design of the breast imaging systems and their unique features.
4. List typical target/filter combinations and discuss their effect on the x-ray spectrum.
5. Describe the characteristics of the different detectors used in breast imaging.
6. Discuss acquisition techniques and selection of acquisition parameters.
7. Discuss breast radiation dosimetry and factors that affect radiation dose.
8. Understand quality control, image quality, and regulatory requirements.

Clinical Application and Problem-Solving:

1. Describe how breast density and thickness variations may affect selection of the different targets and filters available in mammography systems.
2. Associate image quality changes with radiation dose changes (with and without magnification).
3. Understand the factors that influence detectability of microcalcifications and visualization of lesions in mammography.
4. Describe the source of common artifacts and methods to eliminate or reduce their appearance.
5. Understand the mechanism, advantages, and limitations of breast tomosynthesis.
6. Explain Computer-Aided Detection (CAD) and its impact in mammography.
7. Explain how a stereotactic biopsy system is used to localize and extract a sample from a suspected lesion?

Curriculum:

9. Mammography
 - 9.1 Underlying Technology and Physics Principles
 - 9.1.1 Acquisition System
 - 9.1.1.1 Full-Field Digital Mammography [3.0]
 - 9.1.1.2 Stereotactic Biopsy System [2.6]
 - 9.1.1.3 Tomosynthesis [3.0]
 - 9.1.2 System Components
 - 9.1.2.1 Target Materials [3.0]
 - 9.1.2.2 Filter Materials [3.0]
 - 9.1.2.3 Compression Paddles [2.9]
 - 9.1.2.4 Grid [3.0]
 - 9.1.2.5 Magnification Stand [2.4]
 - 9.1.2.6 Automatic Exposure Control (AEC) [3.0]
 - 9.1.2.7 Collimation [2.9]
 - 9.1.2.8 Detectors [2.9]
 - 9.1.3 Physics Principles
 - 9.1.3.1 K-Edge Attenuation [2.9]
 - 9.1.3.2 X-ray Spectrum [2.7]
 - 9.1.3.3 Target/Filter Combinations [3.0]

- 9.1.3.4 Image Contrast and Attenuation of Breast Tissues and Lesions [2.7]
- 9.1.3.5 Breast Compression [3.0]
- 9.1.3.6 Stereotactic Visualization [2.1]
- 9.1.3.7 Principles of Tomosynthesis [2.9]
- 9.2 Effective Use
 - 9.2.1 Clinical Importance
 - 9.2.1.1 Benefits and Risks [3.0]
 - 9.2.1.2 Purpose of Screening and Diagnostic Mammography [3.0]
 - 9.2.1.3 Dedicated Equipment Requirements [3.0]
 - 9.2.1.4 Breast Anatomy [3.0]
 - 9.2.2 Image Acquisition
 - 9.2.2.1 Source-to-Image, Source-to-Object, and Object-to-Detector Distances [2.7]
 - 9.2.2.2 Focal Spot Size [2.9]
 - 9.2.2.3 Collimation [2.4]
 - 9.2.2.4 Chest Wall Coverage [3.0]
 - 9.2.2.5 Heel Effect [2.4]
 - 9.2.2.6 Grid vs. Air Gap [2.6]
 - 9.2.2.7 Magnification [2.9]
 - 9.2.2.8 2D (Mammography) vs. 3D (Tomosynthesis) [2.7]
 - 9.2.2.9 Patient Positioning [2.4]
 - 9.2.2.10 Target/Filter and Acquisition Parameter Selection [2.9]
 - 9.2.3 Image Processing
 - 9.2.3.1 Raw, For-Processing, and For-Display Images [1.9]
 - 9.2.3.2 Computed Aided Detection (CAD) [2.0]
 - 9.2.3.3 Image Compression [2.0]
 - 9.2.4 Workstations, PACS, and Display Requirements [2.6]
- 9.3 Image Characteristics and Artifacts
 - 9.3.1 Detector-Based (Dead or Unread Lines, Ghosting, etc.) [2.6]
 - 9.3.2 Machine-Based (Grid Lines, etc.) [2.7]
 - 9.3.3 Patient-Related (Motion, Positioning, etc.) [2.7]
 - 9.3.4 Image Processing (Lossy Compression, etc.) [2.4]
- 9.4 Safety, Quality Management, and Regulatory Issues
 - 9.4.1 Radiation Dose
 - 9.4.1.1 Entrance Air KERMA [1.4]
 - 9.4.1.2 Average Glandular Dose (AGD) [2.7]
 - 9.4.1.3 Mammography Quality Standards Act (MQSA) Dose Limits [2.9]
 - 9.4.2 Factors Affecting Patient Dose
 - 9.4.2.1 Half-Value Layer (HVL) [2.1]
 - 9.4.2.2 Automatic Exposure Control (AEC), kV, and Target/Filter [2.7]
 - 9.4.2.3 Breast Thickness and Composition [2.7]
 - 9.4.2.4 2D (Mammography) vs. 3D (Tomosynthesis) [2.7]
 - 9.4.3 Quality Management [2.4]
 - 9.4.4 Accreditation Phantom and Quality Control Program [2.6]
 - 9.4.5 Regulatory Issues
 - 9.4.5.1 MQSA and Accreditation Bodies [2.4]
 - 9.4.5.2 Responsibility of Radiologist, Technologist, and Physicist [2.7]
 - 9.4.5.3 Patient and Occupational Protection [1.3]

9.5 Modality-Specific References

1. Ayyala, R.S., Chorlton, M., Behrman, R.H., Kornguth, P.J., and Slanetz, P.J. “Digital mammographic artifacts on full-field system: What are they and how do I fix them?” *Radiographics* 28:1999–2008, 2008.
2. Jayadevan, R., et al. “Optimizing Digital Mammographic Image Quality for Full-Field Digital Detectors: Artifacts Encountered during the QC Process.” *RadioGraphics* 35(7):2080–2089, 2015.
3. Mammography Quality Standards Act and Program. <https://www.fda.gov/radiation-emittingproducts/mammographyqualitystandardsactandprogram/>
4. ACR Accreditation in Mammography. <http://www.acraccreditation.org/Modalities/Mammography>

Example Q&A:

Q1. (Effective Use) What are the minimal images required for locating a lesion in a stereotactic breast biopsy system?

- A. 3
- B. 5
- C. 9
- D. 15

Answer: A

Explanation: During stereotactic breast biopsy, the breast is aligned and compressed by an open-area paddle. After verification with a scout image, two images of the breast are acquired, i.e. at +15 and –15 degrees relative to the 0 degree position on the scout image. Then basic geometry is used to determine the location of the lesion in the 3D coordinate system with the paired images.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q2. (Underlying Technology and Physical Principles) What is the typical focal spot size for contact mammography?

- A. 3.0 mm
- B. 1.0 mm
- C. 0.3 mm
- D. 0.1 mm

Answer: C

Explanation: Mammographic x-ray tubes are typically available with focal spots of 0.1 mm to 0.3 mm. A nominal 0.3 mm large focal spot is used for the routine contact images to obtain the high resolution needed in mammography. A nominal 0.1 mm small focal spot is used for magnification images. Small focal spot size is important since typical microcalcifications are ~0.1 mm. The typical focal spot size for conventional radiography is 0.6 mm to 1.2 mm.

References:

1. R.R. Carlton and A.M. Adler. *Principles of Radiographic Imaging: An Art and a Science*, 5th ed. Cengage Learning, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q3. (Underlying Technology and Physical Principles) What is the advantage of using low kV?

- A. Low radiation dose
- B. Low exposure time
- C. High subject contrast
- D. High spatial resolution

Answer: C

Explanation: At low kV the attenuation difference between different tissues is accentuated due to the increased photoelectric effect. This results in increased subject contrast.

References:

1. R.R. Carlton and A.M. Adler. *Principles of Radiographic Imaging: An Art and a Science*, 5th ed. Cengage Learning, 2012.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q4. (Effective Use) Which of the following is reduced if inadequate compression pressure is applied?

- A. Scattered radiation
- B. Entrance skin exposure
- C. Geometric blur
- D. Image contrast

Answer: D

Explanation: Breast compression is an important part of the mammography examination, which reduces overlapping anatomy, decreases tissue thickness, and reduces inadvertent motion of the breast. Inadequate breast compression will increase scattered x-rays, geometric blurring of anatomic structures, and radiation dose to the breast tissues, resulting in a lower image contrast.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q5. (Underlying Technology and Physical Principles) What is the purpose of aligning the cathode with the chest wall and anode with the nipple?

- A. Achieves uniform exposure
- B. Decreases the focal spot size
- C. Minimizes motion artifact
- D. Reduces acquisition time

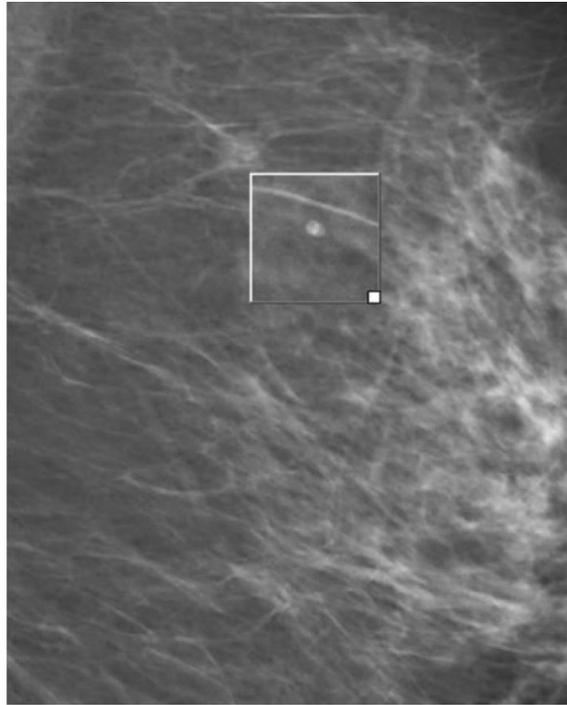
Answer: A – Achieves uniform exposure

Explanation: This position takes advantage of the heel effect, which places the greatest x-ray intensity over the thickest, densest portion of the breast, i.e., the chest wall. This results in a more uniform exposure at the image receptor.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q6. What could be the cause of the degraded image quality seen in this mammogram?



(Image from International Atomic Energy Agency. IAEA Human Health Series 17: Quality Assurance Program for Digital Mammography. IAEA, Vienna pg. 34, 2011.

- A. Low kV
- B. Motion
- C. Contrast
- D. Noise

Answer: B – Motion

Explanation: Patient motion can lead to image blurring.

Reference:

Ayyala, R.S., M. Chorlton, R.H. Behrman, P.J. Kornguth, and P.J. Slanetz. “Digital mammographic artifacts on full-field systems: what are they and how do I fix them?” *Radiographics* 28:1999–2008, 2008.

Q7. (Image Characteristics and Artifacts) What artifact is shown (arrow) in the breast axillary region?



(Image from Ayyala, R.S., M. Chorlton, R.H. Behrman, P.J. Kornguth, and P.J. Slanetz. “Digital mammographic artifacts on full-field systems: what are they and how do I fix them?” *Radiographics* 28:1999–2008, 2008.)

- A. Skin fold
- B. Motion
- C. Antiperspirant
- D. Dead pixel

Answer: C – Antiperspirant

Explanation: Prior to undergoing mammography, patients should be reminded not to wear antiperspirant or skin cream. Antiperspirant artifact is important to recognize, since its appearance can be mistaken for unusual lesions or calcifications in the breast axillary region, possibly leading to unnecessary testing and procedures.

Reference:

Ayyala, R.S., M. Chorlton, R.H. Behrman, P.J. Kornguth, and P.J. Slanetz. “Digital mammographic artifacts on full-field systems: what are they and how do I fix them?” *Radiographics* 28:1999–2008, 2008.

Q8. (Underlying Technology and Physical Principles) The pixel size in digital mammography should be less than

- A. 50 μm
- B. 70 μm
- C. 100 μm
- D. 140 μm

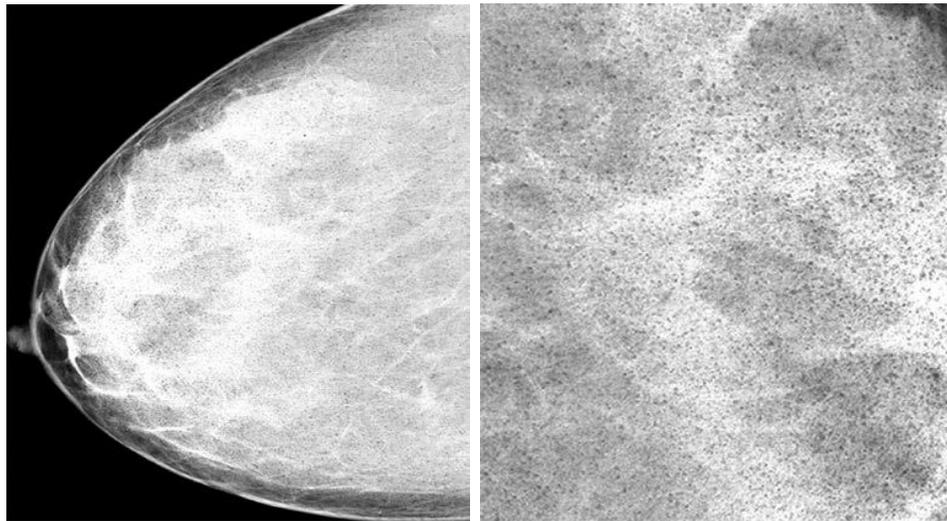
Answer: C – 100 μm

Explanation: Pixel sizes in current digital mammography range between 50 and 100 μm in order to detect microcalcifications, which are specks of calcium hydroxyapatite with diameters as small as 100 μm .

References:

1. Huda, W., *Review of Radiologic Physics*, 4th ed. Wolters Kluwer, 2016
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q9. (Image Characteristics and Artifacts) What is the most likely cause of the artifact shown below?



(Image from Ayyala, R.S., M. Chorlton, R.H. Behrman, P.J. Kornguth, and P.J. Slanetz. “Digital mammographic artifacts on full-field systems: what are they and how do I fix them?” *Radiographics* 28:1999–2008, 2008.)

- A. Dead pixels
- B. Underexposure
- C. Motion
- D. Antiperspirant

Answer: B – Underexposure

Explanation: RCC mammogram obtained at 28 kV and 8.7 mAs shows light regions with dark speckled areas that represent amplified noise. These findings are a result of underexposure with a subsequently low signal-to-noise ratio. The magnified image on the right more clearly shows the findings in the left image. The anatomic signal and noise cannot be differentiated from one another and are, therefore, equally displayed.

Reference:

Ayyala, R.S., M. Chorlton, R.H. Behrman, P.J. Kornguth, and P.J. Slanetz. “Digital mammographic artifacts on full-field systems: what are they and how do I fix them?” *Radiographics* 28:1999–2008, 2008.

Q10. (Safety, Quality Management and Regulatory Issues) What is the radiation dose of 3D tomosynthesis compared to a 2D mammogram?

- A. Comparable
- B. 2 times higher
- C. 3 times higher
- D. 4 or more times higher

Answer: A – Comparable

Explanation: The radiation dose in digital tomosynthesis is comparable to a 2D contact mammogram on a digital system ~1–1.5 mGy AGD on the MQSA phantom depending on manufacturer.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Feng, S.S., Sechopoulos, I. “Clinical digital breast tomosynthesis system: dosimetric characterization.” *Radiology* 263(1):35–42, 2012.

Q11. (Effective Use) Which of the following would be used to perform a 2D screening mammogram on a large dense breast?

- A. W/Mo
- B. Mo/Mo
- C. Rh/Rh
- D. W/Al

Answer: C – Rh/Rh

Explanation: Large dense breasts require higher energies, which are created by using rhodium targets and filters. Tungsten targets with aluminum give a higher energy as well, but are currently only used during tomosynthesis. On some systems higher energies are attained using a tungsten target with a silver filter (W/Ag).

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Module 10: Fluoroscopy and Interventional Imaging

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Describe and identify the basic components of fluoroscopic systems.
2. Explain how the geometric features of a fluoroscopic system contribute to the resulting image.
3. Discuss the differences between flat-panel and image intensifier-based (II) fluoroscopic systems.
4. Describe the different operating modes available in fluoroscopic systems.
5. Discuss the factors that affect image quality in a fluoroscopic system.
6. Discuss the various factors that affect patient dose during a fluoroscopic or interventional procedure.
7. Explain the different radiation dose indicators used in fluoroscopy and limitations in estimating patient skin dose.
8. Describe potential skin injuries from interventional procedures, their dose thresholds, and onset times.
9. Describe artifacts that can occur with image-intensified and flat-panel fluoroscopy systems.
10. Explain federal and state regulations regarding fluoroscopy output rates and potential skin injury.
11. Review relevant regulations (e.g. federal, Joint Commission, state) with respect to fluoroscopic equipment and patient safety.

Clinical Applications and Problem-Solving:

1. List the various clinical applications of fluoroscopic and interventional radiology systems.
2. Understand how to optimize protocol parameters used in various clinical applications.
3. Discuss radiation safety considerations and methods to minimize dose for patients and personnel.
4. Discuss methods to optimize patient dose for specific populations, such as pediatric, bariatric, and pregnant patients.
5. Understand the basic principles and applications of 3-D rotational (cone beam CT) acquisitions.

Curriculum:

10. Fluoroscopy and Interventional Imaging
 - 10.1. Underlying Technology and Physics Principles
 - 10.1.1. System Components [3.0]
 - 10.1.1.1. Tube [3.0]
 - 10.1.1.2. Filtration and Half-Value Layer [2.8]
 - 10.1.1.3. Collimation [3.0]
 - 10.1.1.4. Grids [3.0]
 - 10.1.1.5. Automatic Exposure Rate Control (AERC) [3.0]
 - 10.1.1.6. Detector Systems [3.0]
 - 10.1.1.6.1. Image Intensifier (II) [2.7]
 - 10.1.1.6.2. II Structure [2.2]
 - 10.1.1.6.3. Brightness Gain [2.2]
 - 10.1.1.6.4. Minification (Geometric) Gain [2.0]
 - 10.1.1.6.5. Flux Gain [2.0]
 - 10.1.1.6.6. Field of View (FOV), Electronic Magnification [2.8]
 - 10.1.1.6.7. Flat-panel [3.0]
 - 10.1.1.6.7.1. Detector Technology [2.3]

- 10.1.1.6.7.2. Binning, Electronic Magnification [2.7]
 - 10.1.1.6.8. Comparative strengths and weakness of detection acquisition systems [3.0]
 - 10.1.1.7. Dose Monitoring Equipment [3.0]
 - 10.1.2. Geometry [3.0]
 - 10.1.2.1. Source-to-Image Receptor Distance (SID), Source-to-Object Distance (SOD), and Object-to-Image Receptor Distance (OID) [3.0]
 - 10.1.2.2. Focal Spot Size [2.2]
 - 10.1.2.3. Geometric Magnification [2.8]
 - 10.1.2.4. System Configurations [2.7]
 - 10.1.2.4.1. Over (Remote) vs. Under Table Systems [2.5]
 - 10.1.2.4.2. O-Arms [1.2]
 - 10.1.2.4.3. Bi-Plane [2.3]
 - 10.1.2.4.4. C-Arm (Fixed/Mobile) [3.0]
- 10.2. Effective Use
 - 10.2.1. Operating Modes [3.0]
 - 10.2.1.1. Continuous Fluoroscopy [2.2]
 - 10.2.1.2. High-Dose Rate Fluoroscopy [3.0]
 - 10.2.1.3. Variable Frame-Rate Pulsed Fluoroscopy [3.0]
 - 10.2.1.4. Digital Spot/Photospot Images [3.0]
 - 10.2.1.5. Digital Cine/Runs [3.0]
 - 10.2.1.6. Digital Subtraction Angiography (DSA) [3.0]
 - 10.2.1.7. Cone-beam CT Imaging (3D Rotational Angiography) [2.2]
 - 10.2.1.8. Road Mapping [1.8]
 - 10.2.2. Image Processing and Storage [2.8]
 - 10.2.2.1. Temporal Recursive Filtering/Frame Averaging [2.8]
 - 10.2.2.2. Last-Image Hold and Last-Series Hold [2.8]
 - 10.2.2.3. Edge Enhancement and Smoothing [2.2]
 - 10.2.2.4. Fluoro Frame Recording [3.0]
 - 10.2.2.5. Fluoro Loop Recording [2.5]
 - 10.2.3. Applications
 - 10.2.3.1. Conventional Fluoroscopy [3.0]
 - 10.2.3.2. Interventional Fluoroscopy [3.0]
 - 10.2.3.3. Pediatric Procedures [3.0]
 - 10.2.4. Protocol Optimization [3.0]
 - 10.2.4.1. Acquisition Parameters (e.g., kV, Pulse Rate) [3.0]
 - 10.2.4.2. Contrast Media [3.0]
 - 10.2.4.3. Patient Positioning/Geometry [2.5]
 - 10.2.4.4. Filtration [2.7]
 - 10.2.4.5. Acquisition Mode [2.8]
 - 10.2.4.6. Beam-On Time [3.0]
 - 10.2.4.7. Image Processing [2.8]
 - 10.2.4.8. Electronic Magnification [3.0]
 - 10.2.4.9. Collimation [3.0]
- 10.3. Image Characteristics and Artifacts
 - 10.3.1. Image Quality [3.0]
 - 10.3.1.1. Low-Contrast Resolution [2.5]
 - 10.3.1.2. Spatial Resolution [3.0]

- 10.3.1.3. Temporal Resolution [3.0]
- 10.3.1.4. Noise [2.7]
- 10.3.1.5. Effect of Ancillary Equipment (e.g., VCR) [1.3]
- 10.3.2. Artifacts [2.5]
 - 10.3.2.1. Image Intensifier (II) Specific (e.g., Pincushion) [2.3]
 - 10.3.2.2. Flat Panel Specific (e.g., Dead Pixels) [2.5]
 - 10.3.2.3. Common Artifacts (e.g., Lag) [2.5]
- 10.4. Safety, Quality Management, and Regulatory Issues
 - 10.4.1. Operator Credentialing and Training [2.3]
 - 10.4.2. Quality Control [1.0]
 - 10.4.3. Dose and Dosimetry [3.0]
 - 10.4.4. Federal Regulations [3.0]
 - 10.4.4.1. Dose Rate Limits [3.0]
 - 10.4.4.2. Audible Alarms [3.0]
 - 10.4.4.3. Minimum Source-to-Patient Distance (Cone) [2.2]
 - 10.4.4.4. Interventional Reference Point [3.0]
 - 10.4.4.5. Patient Table and Maximum Half-Value Layer [1.2]
 - 10.4.5. Dose Metrics [3.0]
 - 10.4.5.1. Peak Skin Dose [3.0]
 - 10.4.5.2. Entrance Air Kerma [3.0]
 - 10.4.5.3. Dose-Area-Product (DAP) and KERMA-Area-Product (KAP) [3.0]
 - 10.4.5.4. Cumulative Dose/Air KERMA [3.0]
 - 10.4.5.5. Beam-On Time/Number of Acquisitions [3.0]
 - 10.4.6. Patient Dose Tracking [3.0]
 - 10.4.6.1. The Joint Commission Sentinel Event [3.0]
 - 10.4.6.2. Limitations of Dose Metrics [3.0]
 - 10.4.7. Typical Dose and Dose Rates [3.0]
 - 10.4.8. Dose Dependence on Acquisition Parameters [3.0]
 - 10.4.9. Operator and Staff Dose [3.0]
 - 10.4.9.1. Typical Values [3.0]
 - 10.4.9.2. Optimization [3.0]
 - 10.4.10. Personnel Protection [3.0]
 - 10.4.10.1. Time, Distance, and Shielding [3.0]
- 10.5. Modality-Specific References
 1. Nickoloff, E.L. "AAPM/RSNA Physics Tutorial or Residents: Physics of Flat-Panel Fluoroscopy Systems. Survey of Modern Fluoroscopy Imaging: Flat-Panel Detectors versus Image Intensifiers and More." *Radiographics* 31:591–602, 2011.
 2. Stecker, M.S., Balter, S., Towbin, R.B., et al. "Guidelines for Patient Radiation Dose Management." *J Vasc Interv Radiol* 20:S263–S273, 2009.
 3. Miller, D.L., Balter, S., Cole, P.E., et al. "Radiation Doses in Interventional Radiology Procedures: The RAD-IR Study Part I: Overall Measures of Dose." *J Vasc Interv Radiol* 14:711–727, 2003.
 4. Miller, D.L., Balter, S., Cole, P.E., et al. "Radiation Doses in Interventional Radiology Procedures: The RAD-IR Study Part II: Skin Dose." *J Vasc Interv Radiol* 14:977–990, 2003.

Example Q&A

Q1. (Effective Use) What is best practice for kV settings during DSA?

- A. Mask kV higher
- B. Post-contrast kV higher
- C. Mask and post-contrast kV equal
- D. kV variations do not impact DSA quality

Answer: C – Mask and post-contrast kV equal

Explanation: If the kV changes, there would be incomplete subtraction of stationary anatomy due to differences in attenuation between the mask and post-contrast x-ray beams.

Reference:

Pooley, R.A., McKinney, J.M., Miller, D.A. “Imaging & Therapeutic Technology. The AAPM/RSNA Physics Tutorial for Residents – Digital Fluoroscopy.” *Radiographics* 21:521–534, 2001.

Q2. (Underlying Technical and Physical Principles) What metric best correlates with stochastic risk in fluoroscopy?

- A. Kerma-Area Product (KAP)
- B. Fluoroscopic Exposure Time
- C. Reference Air Kerma
- D. Cumulative Dose

Answer: A – Kerma-Area Product (KAP)

Explanation: Fluoroscopic exposure time is not the best estimate for a patient’s fluoroscopic radiation dose (NCRP 168, Figure 2.2). Air Kerma needs to take into account several factors, including an inverse-square correction as well as an air kerma to skin dose conversion, backscatter factor, etc., to correctly calculate the entrance skin dose. Air Kerma Area Product provides a good estimate of the total x-ray energy imparted to the tissues of the patient, which relates to stochastic effects (NCRP 168, p. 198).

References:

1. NCRP. *NCRP Report No. 168, Radiation Dose Management for Fluoroscopically-Guided Interventional Medical Procedures*. Bethesda, MD: National Council on Radiation Protection and Measurements, 2011.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q3. (Underlying Technical and Physical Principles) What is the goal of the automatic exposure rate control system (AERC)?

- A. Maintain a constant patient skin entrance dose rate
- B. Maintain a constant dose rate to the image receptor
- C. Increase the dose rate to the image receptor for larger patients
- D. Decrease the dose rate to the image receptor for smaller patients

Answer: B – Maintain a constant dose rate to the image receptor

Explanation: The AERC system consists of a feedback loop between the x-ray generator and (roughly speaking) the image receptor. A default dose rate is set at the image receptor that produces images of acceptable brightness and/or signal-to-noise ratio (SNR). As patient anatomical thickness increases (or decreases) for different patient sizes and/or tube angles, the dose rate at the image receptor will suddenly decrease (or increase) with respect to this target. The AERC will immediately signal the x-ray generator to increase (or decrease) the kV/mA, etc. to bring the dose rate back to the set target rate.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q4. (Underlying Technical and Physical Principles) Which dose metric reported in fluoroscopy may have units of Gy*cm²?

- A. Cumulative dose
- B. Peak skin dose
- C. kerma-area product
- D. Effective dose

Answer: C – kerma-area product

Explanation: The units for kerma-area product are dose (e.g., mGy) times area (e.g., cm²) so, mGy*cm².

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q5. (Effective Use) What fluoroscopic modes results in the highest air kerma rate?

- A. Pulsed, 30 pps
- B. Pulsed, 15 pps
- C. Continuous
- D. Cine/Digital Run

Answer: D – Cine/Digital Run

Explanation: Cine/digital run results in the highest patient radiation exposure rate and should be used sparingly. All other factors being equal pulsed fluoroscopy at 15 pps should have a lower dose rate than 30 pps or continuous. Typically, continuous fluoroscopy delivers higher patient radiation exposure rates than pulsed fluoroscopy.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q6. (Effective Use) Under automatic brightness control (ABC) or automatic exposure rate control (AERC) in fluoroscopy, which combination of kV and mA results in the lowest patient skin entrance dose rate?

- A. High kV, low mA
- B. Low kV, high mA
- C. High kV, high mA

Answer: A – High kV, low mA.

Explanation: High-kV x-rays are more penetrating and thus, for the same mA, a greater number reach the image receptor after passing through the patient than low-kV x-rays. Therefore, a lower mA is required to maintain the same target dose rate at the image receptor than for lower-kV x-rays.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q7. (Safety) In fluoroscopy, the x-ray scatter 1 m from a patient is roughly what percent of the patient skin entrance exposure?

- A. 0.001%
- B. 0.01%
- C. 0.1%
- D. 1.0%
- E. 10%

Answer: C – 0.1%.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q8. (Safety, Quality Management, and Regulatory Issues) Which of the following is a stochastic effect that could occur in a high-dose fluoroscopic procedure?

- A. Erythema
- B. Epilation
- C. Desquamation
- D. Dermal necrosis
- E. Carcinogenesis

Answer: E – Carcinogenesis

Explanation: Carcinogenesis is a stochastic radiation effect. Erythema, epilation, desquamation, and dermal necrosis are deterministic effects from excessive radiation exposure.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q9. (Safety, Quality Management, and Regulatory Issues) What is the threshold for The Joint Commission reviewable fluoroscopic sentinel event?

- A. Greater than 2 Gy is delivered to a single field
- B. Greater than 2 Gy is delivered over all fields
- C. Greater than 15 Gy is delivered to a single field
- D. Greater than 15 Gy is delivered to all fields

Answer: C – Greater than 15 Gy is delivered to a single field.

Explanation: According to the Joint Commission standard, a reviewable fluoroscopic sentinel event occurs if the dose exceeds 15 Gy in any single field.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q10. (Safety, Quality Management, and Regulatory Issues) Where should the image receptor be positioned in order to minimize patient dose?

- A. Twice the source to patient surface distance
- B. As close to the patient surface as possible
- C. As far from the patient surface as possible
- D. Half the distance to isocenter

Answer: B – As close to the patient surface as possible

Explanation: Dose reaching the receptor is maximized when the receptor is positioned as close to the patient surface as possible due to the inverse square law. As a result less radiation is necessary to create a sufficient receptor dose.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q11. (Safety, Quality Management, and Regulatory Issues) What is the FDA limit for entrance skin exposure rate in high dose rate exposure mode (i.e., “boost” mode)?

- A. 87 mGy/s (10 R/s)
- B. 87 mGy/min (10 R/min)
- C. 174 mGy/s (20 R/s)
- D. 174 mGy/min (20 R/min)

Answer: D – 174 mGy/min (20 R/min)

Explanation: The FDA limits the maximum entrance skin exposure rate to 174 mGy/min (20 R/min) when using high dose rate exposure mode (AKA, boost mode).

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q12. (Safety, Quality Management, and Regulatory Issues) What is a typical effective dose from an upper gastrointestinal series?

- A. 0.06 mSv
- B. 0.6 mSv
- C. 6 mSv
- D. 60 mSv

Answer: C – 6 mSv

Explanation: The typical effective dose delivered by an upper GI series is 6 mSv (range 1.5 mSv to 12 mSv).

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Mettler, F.A., et al. “Effective doses in radiology and diagnostic nuclear medicine: A catalogue.” *Radiology* 248: 254–263, 2008.

Q13. (Image Quality and Artifacts) Image intensifier (II) type image receptors are most susceptible to what artifact?

- A. Pincushion distortion
- B. Conebeam errors
- C. Dead detector elements
- D. Flat-field artifact

Answer: A – Pincushion Distortion

Explanation: Pincushion distortion is a geometric nonlinear magnification difference at the periphery of the image resulting from the projection of the x-ray beam onto a curved input surface. Pincushion distortion is specific to image intensifier-based fluoroscopic systems. Conebeam errors are CT artifacts. Dead detector elements and flat-field artifacts are specific to flat-panel systems.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q14. (Image Quality and Artifacts)

Flat panel fluoroscopy systems are susceptible to which of the following?

- A. Pincushion Distortion
- B. S-Distortion
- C. Vignetting
- D. Dead Pixels

Answer: D – Dead Pixels

Explanation: Pincushion distortion, vignetting, and s-distortion are specific to image intensifier-based fluoroscopic systems. Only dead pixels are specific to flat panel-based fluoroscopic systems.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q15. (Image Quality and Artifacts)

Increasing what parameter increases the magnitude of S-distortion?

- A. Receptor dose
- B. kV
- C. Field of view
- D. mA

Answer: C – Field of view.

Explanation: S-distortion is due to deviations in the electron trajectories in the image intensifier caused by stray magnetic fields, including the Earth's. These deviations are greatest for the trajectories originating near the edges of the image intensifier and thus produce the largest distortions at the edges of the image. Other parameters listed above do not appreciably impact the extent of S-distortion.

References:

1. Bushberg, J.T., et al. The Essential Physics of Medical Imaging, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. Review of Radiologic Physics, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Module 11: Computed Tomography

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Identify the major components of a multi-detector channel CT system.
2. Describe how a CT image is formed.
3. Define the Hounsfield unit and list typical values for tissues.
4. Describe the advantages and disadvantages of various image reconstruction options.
5. Describe the different operating modes available in CT and discuss when they may be used.
6. Describe the various dose metrics used in CT and provide typical values for common examinations.
7. List the image acquisition parameters and explain how each affects image quality and dose.
8. Compare image quality metrics (e.g., resolution) of CT to other modalities, such as digital radiography.

Clinical Applications and Problem-Solving:

8. Describe how tube current modulation and tube voltage selection affects patient dose.
9. Describe the source of common artifacts and methods to eliminate or reduce their appearance.
10. Describe how CT protocols could be optimized for different age/size patients (image quality/dose tradeoff).
11. Discuss the limitations of CT dose metrics in estimating patient dose.

Curriculum:

11. Computed Tomography (CT)
 - 11.1. Underlying Technology and Physics Principles
 - 11.1.1. System Components
 - 11.1.1.1. Gantry/Beam Geometry [2.5]
 - 11.1.1.2. Tube (Fixed and Flying Focal Spot) [2.1]
 - 11.1.1.3. Beam Filtration and Shaping (Bow-Tie) Filters [2.3]
 - 11.1.1.4. Collimation [3.0]
 - 11.1.1.5. Detector Types and Configuration [2.9]
 - 11.1.2. System Types
 - 11.1.2.1. Multi-Detector Channel [2.8]
 - 11.1.2.2. Dual Source [1.8]
 - 11.1.2.3. Flat-Panel Cone-Beam (See Also Fluoroscopy) [1.0]
 - 11.1.3. Acquisition Modes
 - 11.1.3.1. Localizer Radiograph (Scout, Surview, Topogram, Scanogram, etc.) [2.6]
 - 11.1.3.2. Axial/Sequential [2.5]
 - 11.1.3.3. Helical/Spiral [2.6]
 - 11.1.3.4. Cardiac/Respiratory Gated [2.4]
 - 11.1.3.5. Dynamic Scan Mode (Shuttle, Jog, Adaptive 4D, etc.) [1.4]
 - 11.1.3.6. CT Fluoroscopy [1.1]
 - 11.1.3.7. Dual Source and Dual Energy [1.9]
 - 11.1.4. Image Acquisition Parameters
 - 11.1.4.1. Tube Voltage (kV) [3.0]
 - 11.1.4.2. Tube Current (mA) [3.0]
 - 11.1.4.3. Rotation Time [3.0]

- 11.1.4.4. Tube Current-Time Product (mAs) and Effective mAs [3.0]
- 11.1.4.5. Pitch [3.0]
- 11.1.4.6. Detector Configuration and Beam Width [3.0]
- 11.1.4.7. Scan and Display Field of View [3.0]
- 11.1.4.8. Image Quality Parameters (Noise Index, Reference mAs, etc.) [3.0]
- 11.1.5. Image Reconstruction
 - 11.1.5.1. Sinogram and Reconstructions [2.4]
 - 11.1.5.2. Filtered-Back Projection [2.6]
 - 11.1.5.3. Statistical and Model-Based Iterative Reconstruction [2.6]
 - 11.1.5.4. Reconstruction Filters/Convolution Kernels [2.6]
 - 11.1.5.5. Helical Reconstruction and Interpolation [1.3]
 - 11.1.5.6. CT Number/Hounsfield Unit [3.0]
 - 11.1.5.7. Reconstruction Thickness and Interval [2.9]
 - 11.1.5.8. Reconstruction Field of View [2.6]
- 11.2. Effective Use
 - 11.2.1. Clinical Applications and Protocols
 - 11.2.1.1. Automatic Tube Current Modulation [3.0]
 - 11.2.1.2. Automatic kV Selection [3.0]
 - 11.2.1.3. Patient Size/Age Technique Adjustments [2.9]
 - 11.2.1.4. Single vs. Multi-Phase Exams [2.6]
 - 11.2.1.5. Perfusion CT [2.4]
 - 11.2.1.6. Cardiac CT [2.5]
 - 11.2.1.7. CT Angiography [2.4]
 - 11.2.1.8. Dual Energy CT [1.9]
 - 11.2.2. Typical Tissue Hounsfield Units and Quantitative Use [3.0]
 - 11.2.3. Factors Affecting Image Quality and Dose
 - 11.2.3.1. Image Acquisition Parameters [3.0]
 - 11.2.3.1.1. Respiratory/Cardiac Gating [2.3]
 - 11.2.3.1.2. Dual Source/Dual Energy [2.1]
 - 11.2.3.1.3. Number of Phases (e.g., Pre- and Post-contrast) [2.0]
 - 11.2.3.2. Image Reconstruction Parameters [2.6]
 - 11.2.3.3. Patient Size and Centering [2.8]
 - 11.2.3.4. Patient Dose Reduction [3.0]
 - 11.2.3.4.1. Organ Dose Modulation [1.8]
 - 11.2.3.4.2. Patient Shielding [1.1]
- 11.3. Image Characteristics and Artifacts
 - 11.3.1. Spatial, Contrast, and Temporal Resolution [2.9]
 - 11.3.2. Signal-to-Noise Ratio (SNR) and Contrast-to-Noise Ratio (CNR) [2.4]
 - 11.3.3. Artifacts and Mitigation [3.0]
 - 11.3.3.1. Patient-Related (Motion, Metal, etc.) [2.9]
 - 11.3.3.2. Scanner-Related (Ring Artifact, Undersampling, etc.) [2.9]
 - 11.3.4. Image Processing and Image Display [2.0]
 - 11.3.4.1. Window and Level Control [2.6]
 - 11.3.4.2. Multi-planar Reconstruction (MPR) [2.4]
 - 11.3.4.3. Maximum Intensity Projection (MIP) [2.0]
 - 11.3.4.4. 3D Volume and Surface Rendering [1.4]
 - 11.3.4.5. Overlays (Dual Energy and Perfusion) [1.4]
 - 11.3.4.6. Virtual Fly Through [1.0]

11.4. Safety, Quality Management, and Regulatory Issues

11.4.1. Dose Descriptors [3.0]

11.4.1.1. Computed Tomography Dose Indices (CTDI, CTDIvol, etc.) [3.0]

11.4.1.2. Dose-Length Product (DLP) [3.0]

11.4.1.3. Organ Dose [1.5]

11.4.1.4. Size-Specific Dose Estimate (SSDE) [2.4]

11.4.1.5. Effective Dose and k-factors [2.6]

11.4.2. Typical Dose Values [3.0]

11.4.3. Adult, Pediatric, and Bariatric Protocol Review and Optimization [2.6]

11.4.4. Quality Control/Assurance [2.0]

11.4.5. Dose Monitoring and Reporting [2.0]

11.4.6. Accreditation and Regulatory Requirements [1.6]

11.4.6.1. American College of Radiology (ACR) [1.6]

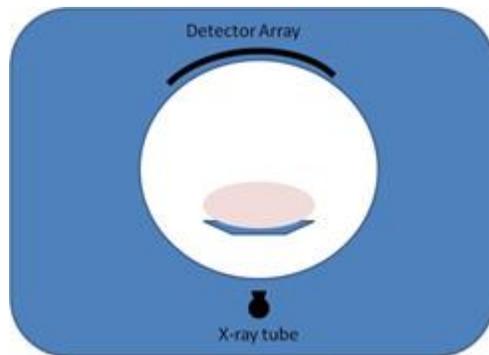
11.4.6.2. The Joint Commission (TJC) 1.0]

11.5. Modality-Specific References

1. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009.
2. American College of Radiology, CT Accreditation Program Requirements. <http://www.acraccreditation.org/modalities/ct>.

Example Q&A:

Q1. (Effective Use) What image quality parameter may be reduced if a patient scan is conducted using tube-current modulation and the localizer image is acquired with the patient positioned below isocenter, as shown in the image below?



(Image courtesy of Karen Brown, Penn State College of Medicine)

- A. Low-contrast visibility
- B. Detail
- C. Quantum noise
- D. Temporal resolution

Answer: C – Quantum noise

Explanation: With the tube stationary under the patient and the patient positioned below isocenter for the acquisition of the scout view, the patient will appear larger than actual size, and a higher tube current will be used. Higher tube current will result in less quantum noise and, therefore, increased low-contrast

visibility. Patient dose will increase proportionally with increased tube current. Spatial and temporal resolution will not be affected by a change in tube current.

References:

1. McNitt-Gray, M. "Tube Current Modulation Approaches: Overview, Practical Issues and Potential Pitfalls." Presented at AAPM 2011 Summit on CT Dose, Denver, CO, 2011.
2. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009.

Q2. (Safety, Quality Management and Regulatory Issues) Match the American College of Radiology CT Accreditation CTDI_{vol} Dose Reference Level to the appropriate facility protocol.

- | | |
|-----------|-------------------------------|
| A. 75 mGy | 1. Adult Body |
| B. 35 mGy | 2. Adult Head |
| C. 25 mGy | 3. Pediatric Body (40–50 lbs) |
| D. 15 mGy | 4. Pediatric Head (1 yr) |

Answer: A.2, B.4, C.1, D.3

Explanation: The American College of Radiology reference levels are set at the values above and are used to help facilities identify situations where dose reduction measures may be indicated.

Reference:

1. American College of Radiology, CT Accreditation Program Requirements, November 2013.
<http://www.acraccreditation.org/modalities/ct>

Q3. (Effective Use) An increase in what parameter can improve visibility of low-contrast structures in a CT image without increasing radiation dose to the patient?

- A. Tube current
- B. Rotation time
- C. Slice thickness
- D. Increase kV

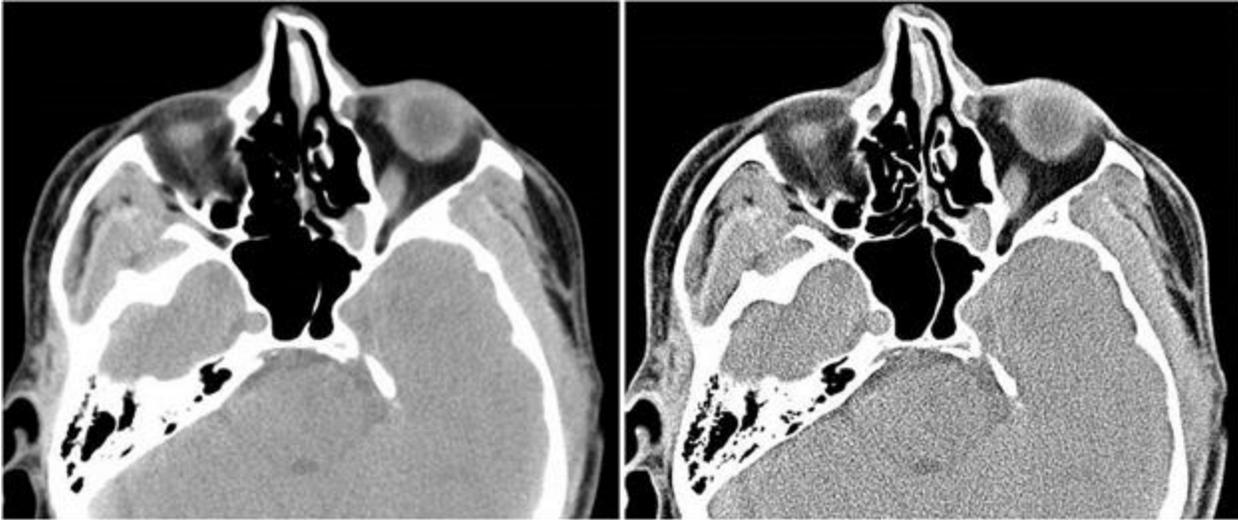
Answer: C –Slice thickness

Explanation: Increasing the reconstructed slice thickness will result in more signal per voxel, which will reduce noise and improve low-contrast visibility. Slice thickness is a reconstruction parameter and therefore does not affect dose to the patient. The disadvantage of a larger reconstructed slice thickness is more partial volume averaging and reduced spatial resolution.

References:

1. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q4. (Effective Use) What parameter was most likely changed from image A to produce image B?



(Image courtesy of William F. Sensakovic, PhD)

- A. Beam energy
- B. Tube current
- C. Gantry angle
- D. Convolution kernel

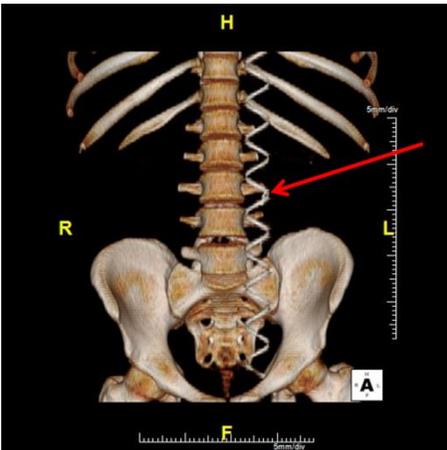
Answer: D – Convolution kernel

Explanation: The image on the left is less noisy, but it also demonstrates a higher degree of blurring (lower resolution). Decreasing kV or mAs will increase image noise; however, neither substantially changes spatial resolution. Changing the gantry angle would create oblique sections. Changing the convolution kernel (AKA, reconstruction filter) changes the spatial frequencies left out during image reconstruction. This simultaneously alters both noise and resolution.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q5. (Image Characteristics and Artifacts) What is cause of the artifact indicated by the arrow in the volume rendered image below?



(Image courtesy of Kevin Moser, PhD., Penn State Milton S. Hershey Medical Center)

- A. Patient motion
- B. Beam hardening
- C. Poor detector calibration
- D. Partial volume averaging

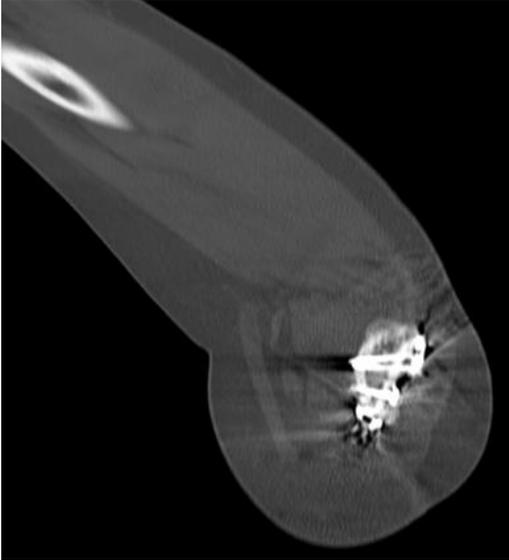
Answer: C – Poor detector calibration

Explanation: On a 3D volume rendered image as shown above, poor detector calibration will appear as a helix as the signal variation from poor detector calibration propagates through the imaged volume. In an axial image acquired with a helical scan, poor detector calibration will appear as a partial ring artifact. If the study is acquired sequentially, a full ring artifact will be seen on an axial image.

References:

1. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q6. (Image Characteristics and Artifacts) Which of the following actions would you take to reduce the artifact in the image shown in the figure below?



(Courtesy of Karen Brown, Penn State College of Medicine)

- A. Perform an air calibration
- B. Increase pitch
- C. Increase beam collimation
- D. Increase tube voltage

Answer: D – Increase tube voltage

Explanation: The image displays streaking artifact due to the presence of metal within the patient anatomy being imaged. Increasing the kV will result in higher x-ray beam energy and increased penetration of the beam through the metal, which will reduce streaking. Increasing collimation will result in more partial volume averaging, which may enhance streaking. To minimize metal artifacts, use narrow collimation. Air calibrations are done to correct detector settings/uniformity. Reducing the pitch would provide more sampling of the tissue and may reduce streaking as well.

References:

1. Lee, M.J., S. Kim, S.A. Lee, H.T. Song, Y.M. Huh, D.H. Kim, S.H. Han, and J.S. Suh. “Overcoming artifacts from metallic orthopedic implants at high-field-strength MR imaging and multi-detector CT.” *RadioGraphics* 27:791–803, 2007.
2. Kalender, W. *Computed Tomography: Fundamentals, System Technology, Image Quality, Applications*, 2nd ed. Erlangen: Publicis Corporate Publishing, 2005.

Q7. (Underlying Technology and Physical Principles) What acquisition parameter may alter the CT number (Hounsfield Unit)?

- A. mA
- B. Collimation
- C. Rotation time
- D. kV

Answer: D – kV

Explanation: CT number (Hounsfield Unit) calculations are based on the difference in linear attenuation coefficient measured for a given voxel compared to the linear coefficient of water. Linear attenuation coefficients will vary with tissue composition and beam energy. Some tissue CT numbers, such as adipose and soft tissue, may only vary slightly with changes in kV, while others (e.g., contrast media) will vary more substantially.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q8. (Underlying Technology and Physical Principles) What gantry/beam geometry is used in modern multi-detector channel CT scanners?

- A. Translate-rotate
- B. Rotate-rotate
- C. Rotate-stationary
- D. Stationary-translate

Answer: B – Rotate-rotate

Explanation: Modern CT scanners use a rotate-rotate gantry/beam geometry. The x-ray tube rotates around the gantry while emitting a fan or cone beam that is intercepted by an array of detectors rotating on the gantry opposite to the x-ray tube.

References:

1. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q9. (Effective Use) Match the typical CT number (Hounsfield Unit) on the left to the appropriate healthy tissue as shown in the image below.



(Image courtesy of Karen Brown, Penn State College of Medicine)

- | | |
|-------------|---|
| 1. -1000 HU | A |
| 2. -120 HU | B |
| 3. 140 HU | C |
| 4. 800 HU | D |

Answer: A.1, B.3, C.2, D.4

Explanation: CT numbers are normalized to water, which means the CT number of water should be at or near zero. Tissues more attenuating than water will have higher CT numbers (positive) and tissues that are less attenuating than water will have lower (negative) CT numbers.

References:

1. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q10. (Safety, Quality Management and Regulatory Issues) What CT exam typically results in the highest study $CTDI_{vol}$?

- A. Routine abdomen
- B. High resolution chest
- C. Cardiac CTA
- D. Brain perfusion

Answer: D – Brain perfusion

Explanation: During a perfusion scan, the same anatomy is repeatedly imaged in real time while contrast agent is being injected. Typical brain perfusion scans may involve the acquisition of 30 to 50 scans at the same anatomical location resulting in displayed $CTDI_{vol}$ values ranging from 150 to 250 mGy.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q11. (Safety, Quality Management and Regulatory Issues) According to American College of Radiology accreditation standards, at what frequency should CT scanners be tested to evaluate for artifacts?

- A. Daily
- B. Weekly
- C. Monthly
- D. Quarterly

Answer: A – Daily

Explanation: The ACR requires the technologist to conduct an axial scan of a uniform phantom on a daily basis to evaluate for artifacts. The artifact test is also completed annually by the medical physicist.

Reference:

1. American College of Radiology, CT Accreditation Program Requirements, November 2013.

Q12. (Image Characteristics and Artifacts) What factor influences in-plane spatial resolution?

- A. Detector width
- B. Pitch
- C. Tube voltage
- D. Display field of view

Answer: D – Display field of view

Explanation: The selected display field of view (FOV) determines pixel size. As pixel size decreases, in-plane spatial resolution improves.

References:

1. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Module 12: Ultrasound

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Identify common characteristics of sound wave propagation and ultrasound interactions with matter.
2. Describe the basic design of ultrasound transducers, and explain the principles of beam formation.
3. Describe the different types of array transducers.
4. Describe the principle of real-time pulse-echo imaging.
5. Identify the function of commonly used operation (or acquisition) settings on an ultrasound system.
6. Describe transducer design and acquisition parameters that affect image quality.
7. Describe the Doppler principle and its applications in various Doppler imaging modes.
8. Understand the principles of advanced ultrasound technologies, such as harmonic imaging, extended field of view, compound imaging, 3D/4D ultrasound, and elastography.
9. Delineate the mechanisms for producing ultrasound bioeffects, and describe the significance of the mechanical index and thermal index parameters.

Clinical Applications and Problem Solving:

1. Discuss the appropriate uses of different types and frequencies of transducers for clinical applications.
2. Describe how to adjust scan parameters to optimize image quality for different clinical applications.
3. Identify common artifacts in ultrasound, their causes, and mitigation strategies.
4. Discuss the different modes of Doppler ultrasound and when they can be appropriately used.
5. Discuss risks versus benefits of using ultrasound in various clinical areas, especially in obstetrics.

Curriculum:

12. Ultrasound

12.1. Underlying Technology and Physics Principles

- 12.1.1. Basic Sound Wave Concepts [3.0]
 - 12.1.1.1. Sound Wave Propagation [3.0]
 - 12.1.1.2. Definition of Sound and Ultrasound [2.4]
 - 12.1.1.3. Properties of Longitudinal and Transverse Waves [2.6]
- 12.1.2. Sound Wave Properties [3.0]
 - 12.1.2.1. Wavelength, Frequency, Period, Speed, and Velocity [3.0]
 - 12.1.2.2. Density and Pressure Changes in Materials [3.0]
 - 12.1.2.3. Particle Motion and Particle Velocity [2.8]
 - 12.1.2.4. Compressibility and Elasticity [3.0]
 - 12.1.2.5. Dependence of Sound Speed on Medium and Properties [3.0]
- 12.1.3. Power and Intensity [3.0]
 - 12.1.3.1. Decibel Scale [2.2]
 - 12.1.3.2. Relationship between Intensity and Pressure [2.6]

- 12.1.4. Interactions of Ultrasound Waves with Matter [2.8]
 - 12.1.4.1. Acoustic Impedance [3.0]
 - 12.1.4.2. Relationship to Density, Speed, and Compressibility [3.0]
 - 12.1.4.3. Impedance Changes at Tissue Interfaces [3.0]
- 12.1.5. Reflection, Refraction, and Transmission [3.0]
 - 12.1.5.1. Role of Impedance [2.8]
 - 12.1.5.2. Reflection Coefficient [1.2]
 - 12.1.5.3. Normal and Oblique Incidence [2.6]
 - 12.1.5.4. Specular and Diffuse Reflection [3.0]
 - 12.1.5.5. Transmission [3.0]
- 12.1.6. Scattering, Absorption, and Attenuation [3.0]
 - 12.1.6.1. Hyperechoic, Hypoechoic, Isoechoic, and Anechoic [3.0]
 - 12.1.6.2. Relationship to Frequency and Scatterer Size [3.0]
 - 12.1.6.3. Rayleigh Scattering (Blood Cells) [1.6]
 - 12.1.6.4. Constructive and Destructive Interference [2.4]
 - 12.1.6.5. Speckle [2.8]
 - 12.1.6.6. Attenuation Causes and its Relationship to Sound Properties [3.0]
 - 12.1.6.7. Attenuation Coefficients [3.0]
- 12.1.7. Transducer Components and Arrays [3.0]
 - 12.1.7.1. Piezoelectric Materials [2.6]
 - 12.1.7.2. Transducer Construction and Operation [3.0]
 - 12.1.7.3. Resonance and Nonresonance (Multifrequency) Transducers [2.2]
 - 12.1.7.4. Linear and Curvilinear Arrays [2.8]
 - 12.1.7.5. Phased Arrays [2.2]
 - 12.1.7.6. Annular Arrays [1.2]
 - 12.1.7.7. 1.5D, 2D, and 3D Arrays [2.2]
 - 12.1.7.8. Intra-Cavitary Transducers [1.0]
 - 12.1.7.9. Intra-Vascular Transducers [1.0]
- 12.1.8. Beam Propagation Patterns [2.2]
 - 12.1.8.1. Near and Far Fields [2.6]
 - 12.1.8.2. Focused Transducers [3.0]
 - 12.1.8.3. Side and Grating Lobes [3.0]
- 12.1.9. Transducer Array Beam Formation and Focusing [2.2]
 - 12.1.9.1. Linear and Sector Scanning [2.2]
 - 12.1.9.2. Transmit and Receive Focusing [2.2]
 - 12.1.9.3. Beam Steering [2.2]
 - 12.1.9.4. Beam Shaping [2.8]
- 12.2. Effective Use
 - 12.2.1. Pulse-Echo Imaging [2.8]
 - 12.2.1.1. Pulse-Repetition Period, Frequency, and Duty Cycle [2.8]
 - 12.2.1.2. Field of View and Maximum Depth [3.0]
 - 12.2.1.3. Frame Rate [3.0]
 - 12.2.2. Image Data Acquisition [2.6]
 - 12.2.2.1. Signal Acquisition Process [1.6]
 - 12.2.2.2. Time-Gain (or Depth-Gain) Compensation [3.0]
 - 12.2.3. 2D- Image Display and Processing [3.0]
 - 12.2.4. Display Modes [2.4]
 - 12.2.4.1. A-Mode, B-Mode, and M-Mode [2.8]

- 12.2.5. Image Frame Rate [2.8]
 - 12.2.5.1. Depth Setting [2.8]
 - 12.2.5.2. Transmit Focal Zones [2.8]
 - 12.2.5.3. Sector Size and Line Density [2.8]
- 12.2.6. Image Processing [2.2]
 - 12.2.6.1. Pre-Processing and Post-Processing [1.2]
 - 12.2.6.2. Noise and Speckle Reduction [2.8]
 - 12.2.6.3. Distance, Area, and Volume Measurements [2.4]
- 12.2.7. Doppler Ultrasound [3.0]
 - 12.2.7.1. Doppler Theory [3.0]
 - 12.2.7.2. Spectral Analysis [2.8]
 - 12.2.7.3. Flow Dynamics (e.g., Laminar and Plug) [2.2]
 - 12.2.7.4. Continuous Wave (CW) Doppler [2.6]
 - 12.2.7.5. Pulsed Doppler [2.8]
 - 12.2.7.6. Duplex Scanning [2.8]
 - 12.2.7.7. Color Flow Imaging [2.8]
 - 12.2.7.8. Power Doppler [2.8]
- 12.2.8. Special US Imaging [2.8]
 - 12.2.8.1. Compound Imaging [3.0]
 - 12.2.8.2. Harmonic Imaging [3.0]
 - 12.2.8.3. Three-Dimensional (3D) Imaging [1.4]
 - 12.2.8.4. Time-Dependent Imaging (4D) [1.2]
 - 12.2.8.5. Elastography [2.0]
- 12.3. Image Characteristics and Artifacts
 - 12.3.1. Image Quality Metric [3.0]
 - 12.3.1.1. Spatial Resolution: Axial, Lateral, Elevational [3.0]
 - 12.3.1.2. Temporal Resolution [3.0]
 - 12.3.1.3. Image Contrast, Noise, CNR [3.0]
 - 12.3.2. Image Artifacts [3.0]
 - 12.3.2.1. Transducer (e.g., Grating Lobes, etc.) [3.0]
 - 12.3.2.2. Propagation (e.g., Shadowing, Ring Down, etc.) [3.0]
 - 12.3.2.3. Doppler (e.g., Twinkle, Flash, Flow Ambiguity, etc.) [3.0]
- 12.4. Safety, Quality Management, and Regulatory Issues
 - 12.4.1. Mechanisms and Limits for Bioeffects [3.0]
 - 12.4.1.1. Heating [3.0]
 - 12.4.1.2. Cavitation [2.2]
 - 12.4.1.3. Thermal Indices (TI) [2.8]
 - 12.4.1.4. Mechanical Index (MI) [2.8]
 - 12.4.2. Acoustic Power [2.8]
 - 12.4.3. Intensity Measures of Ultrasound Energy Deposition [1.6]
 - 12.4.3.1. Spatial Average/Temporal Average Intensity ISATA [1.2]
 - 12.4.3.2. Spatial Peak/Temporal Average Intensity ISPTA [1.2]
 - 12.4.3.3. Spatial Peak/Pulse Average Intensity ISPPA [1.2]
 - 12.4.3.4. Spatial Peak/Temporal Peak Intensity I_{SPTP} [1.2]
 - 12.4.4. Pregnant Patient and Pediatric Protocols [1.6]
 - 12.4.4.1. Acceptable Thermal Index of Bone (TIB) and Thermal Index of Cranial Bone (TIC) limits [2.6]
 - 12.4.4.2. Current Clinical Statements on Ultrasound Safety [1.6]

12.4.5. Ultrasound Quality Control and Quality Assurance [1.6]

12.4.6. Accreditation [2.0]

12.5. Modality-Specific References

1. Kremkau, F.W. *Sonography: Principles and Instruments*, 9th ed. St. Louis, MO: Elsevier, 2015.
2. Baad, M., et al. "Clinical Significance of US Artifacts." *RadioGraphics* 37:1408–1423, 2017.
3. Szabo, T.L., et al. "Ultrasound Transducer Selection in Clinical Imaging Practice." *J Ultrasound Med* 32:573–582, 2013.
4. Anvari, A., et al. "A Primer on the Physical Principles of Tissue Harmonic Imaging." *Radiographics* 35:1955–1964, 2015.

Example Q&A:

Q1. (Image Characteristics and Artifacts) What property in this cyst image causes the posterior enhancement?



(Courtesy Adel Mustafa, PhD)

- A. Increased attenuation
- B. Decreased attenuation
- C. Increased speed of sound
- D. Decreased speed of sound

Answer: B – Decreased attenuation

Explanation: Cysts attenuate less and are anechoic. Since there are no internal echoes produced, the area distal to them receives a beam of higher intensity than the beam traveling a corresponding distance in soft tissue. So the region behind them produces a brighter echo, which is posterior enhancement. An increase or decrease in speed of sound in the cyst will cause the cyst posterior wall to appear closer or farther away from its actual depth, which is not the case in this image.

References:

1. Hedrick, P., et al. *Ultrasound Physics and Instrumentation*, 4th ed. Mosby, 2005.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
3. Prabhu, S., et al. "Ultrasound artifacts classification, applied physics with illustrations, and imaging appearances." *US Quarterly* 30: 2, June 2014.

Q2. (Underlying Technology and Physical Principles) Determine the attenuation of a 5 MHz ultrasound beam in soft tissue traveling round trip to a depth of 2 cm assuming 100% reflection at the interface.

- A. 3 dB
- B. 5 dB
- C. 7.5 dB
- D. 10 dB

Answer: D – 10 dB

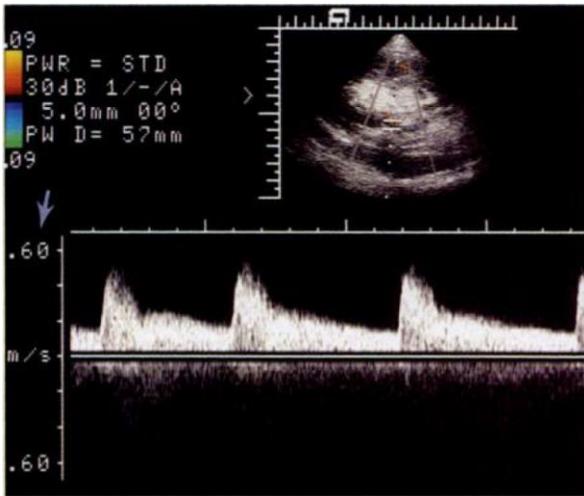
Explanation: Using the rule of the thumb for attenuation in soft tissue of 0.5 dB/cm/MHz, the attenuation would be:

$$0.5 \text{ dB/cm/Hz} \times 5 \text{ MHz} \times 4 \text{ cm} = 10 \text{ dB}$$

References:

1. Anthony Brinton Wolbarst, *Physics of Radiology*, 2nd Ed., Madison, Wisconsin: Medical Physics Publishing, 2005.
2. Hedrick, P., et al. *Ultrasound Physics and Instrumentation*, 4th Ed. Mosby, 2005.

Q3. (Effective Use) What do the changes in brightness of the spectral Doppler waveform shown in the image below represent?



(Image credit: Pozniak, M.A., et al. “Spectral and Color Doppler Artifacts.” *RadioGraphics* 12:35–44, 1992.

- A. Changes blood velocity
- B. Variations in signal intensity
- C. Pulsatile flow
- D. Larger calculated Doppler shift

Answer: B – Variations in signal intensity

Explanation: In spectral Doppler, changes in blood velocity calculated from the Doppler shift are displayed along the vertical axis and time along the horizontal axis. The brightness of the grayscale or color displayed at a particular point in time represents the intensity of the Doppler signal, which is proportional to the number of blood cells moving at the displayed velocity.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Anthony Brinton Wolbarst, *Physics of Radiology*, 2nd ed., Madison, Wisconsin: Medical Physics Publishing, 2005.

Q4. (Effective Use) What is a benefit of using harmonic imaging compared to conventional imaging?

- A. Increased mechanical index
- B. Enhanced contrast
- C. Higher frame rates
- D. Better depth information

Answer: B – Enhanced contrast

Explanation: When ultrasound waves interact with tissue, different tissues distort the wave differently, producing harmonic frequencies as integral multiples of the fundamental frequency. The resultant returning echo has a harmonic frequency, which is selectively listened to by the transducer receiver. This allows removal of echo clutter from the fundamental frequency reflections, producing a native tissue harmonic image with enhanced sensitivity to tissue variations and improved contrast. Harmonic imaging is commonly used with microbubbles contrast agents.

References:

1. Hedrick, P., et al. *Ultrasound Physics and Instrumentation*, 4th ed. Mosby, 2005.
2. Anthony Brinton Wolbarst, *Physics of Radiology*, 2nd ed., Madison, Wisconsin: Medical Physics Publishing, 2005.

Q5. (Effective Use) What is an advantage of using a curvilinear transducer instead of a linear transducer?

- A. Increased attenuation
- B. Improved resolution
- C. Expanded field of view
- D. Higher Frame Rates

Answer: C – Expanded field of view

Explanation: Curved-array transducers have a large field of view and better penetration of soft tissue, however the scan lines diverge deep in tissue and often interpolation is needed to fill in non-traversed pixels in the images.

References:

1. Stewart C. Bushong, *Radiologic Science for Technologists*, 10th ed. St. Louis: Mosby, 2013.
2. Kruskal, J.B., P.A. Newman, L.G. Sammons, and R.A. Kane. “Optimizing Doppler and color flow US: application to hepatic sonography.” *Radiographics* 24:657–75, 2004.

Q6. (Effective Use) In Doppler ultrasound, what angle is within the preferred range to obtain accurate velocity measurements?

- A. 15 degrees
- B. 25 degrees
- C. 55 degrees
- D. 75 degrees

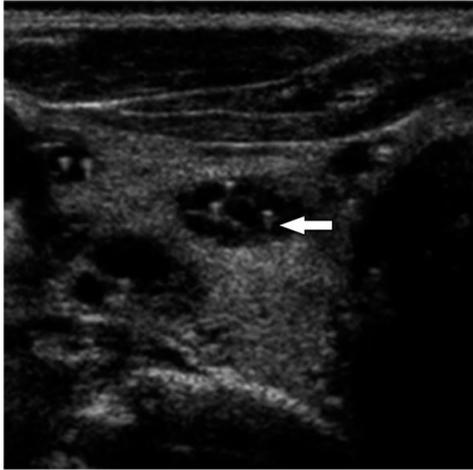
Answer: C – 55 degrees

Explanation: Within a 45- to 60-degree angle, a linear relation exists between the Doppler shift and velocity. Outside this range less Doppler shift and increased sensitivity to angle variation will cause inaccurate velocity estimate.

References:

1. Hindi, A., et al. “Artifacts in Diagnostic Ultrasound.” *Reports in Medical Imaging* 6:29–48, 2013.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
3. Kruskal, J.B., P.A. Newman, L.G. Sammons, and R.A. Kane. “Optimizing Doppler and color flow US: application to hepatic sonography.” *Radiographics* 24:657–75, 2004.

Q7. (Image Characteristics and Artifacts) Identify the artifact in this ultrasound image?



(Image Credit: Baad, M., et al. “Clinical Significance of US Artifacts.” *RadioGraphics* 37:1408–1423, 2017.)

- A. Mirror image artifact
- B. Shadowing artifact
- C. Comet tail artifact
- D. Side lobe artifact

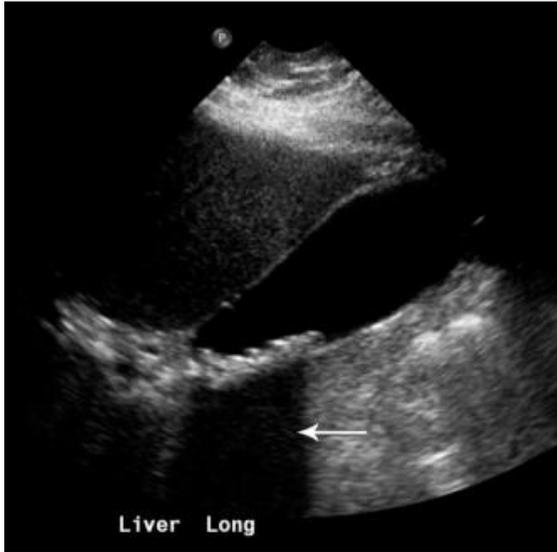
Answer: C – Comet tail artifact

Explanation: Comet tail artifact is the result of multiple reflections between closely spaced reflectors creating reverberations. The multiple signals received by the transducer create a band of signal in the image.

References:

1. Hedrick, P., et al. *Ultrasound Physics and Instrumentation*, 4th ed. Mosby, 2005.
2. Owen, C.C. and L.E. Bilhartz. “Gallbladder polyps, cholesterosis, adenomyomatosis, and acute acalculous cholecystitis.” *Semin. Gastrointest. Dis.* 14:178–88, 2003.
3. Prabhu, S., et al. “Ultrasound artifacts classification, applied physics with illustrations, and imaging appearances.” *US Quarterly* 30: 2, June 2014.

Q8. (Image Characteristics and Artifacts) Identify the artifact seen with gallstones in the figure?



(Image Credit: Feldman, M.K., et al. "US Artifacts." *RadioGraphics* 29:1179–1189, 2009.)

- A. Comet tail
- B. Mirror image
- C. Shadowing
- D. Twinkle

Answer: C – Shadowing

Explanation: Shadowing artifacts are classified as dirty or clean. Shadowing below large, highly attenuating structures usually has well-defined margins and is classified as clean. Shadowing caused by gas or air often results in shadowing with less-defined margins and is called dirty shadowing.

References:

1. Ammar Hindi, et al. "Artifacts in diagnostic Ultrasound." *Reports in Medical Imaging*, 6:29–48, 2013.
2. Stewart C. Bushong, *Radiologic Science for Technologists*, 10th ed. St. Louis: Mosby, 2013.
3. Prabhu, S., et al. "Ultrasound artifacts classification, applied physics with illustrations, and imaging appearances." *US Quarterly* 30: 2, 2014.

Q9. (Image Characteristics and Artifacts) Name the artifact identified by the arrow?



(Image Credit: Baad, M., et al. “Clinical Significance of US Artifacts.” *RadioGraphics* 37:1408–1423, 2017)

- A. Mirror image
- B. Speed displacement
- C. Grating lobe
- D. Enhancement

Answer: A – Mirror image

Explanation: A mirror image artifact arises from multiple beam reflections between a mass and a strong reflector such as the diaphragm. Multiple echoes result in the creation of a mirror image of the mass beyond the strong reflector.

References:

1. Sandler, M.A., B.L. Madrazo, et al. “Ultrasound case of the day. Duplication artifact (mirror image artifact).” *Radiographics* 7:1025, 1987.
2. Hedrick, P., et al. *Ultrasound Physics and Instrumentation*, 4th ed. Mosby, 2005.
3. Prabhu, S., et al. “Ultrasound artifacts classification, applied physics with illustrations, and imaging appearances.” *US Quarterly* 30: 2, June 2014.
4. Bushong, S.C. *Radiologic Science for Technologists*, 10th ed. St. Louis: Mosby, 2013.

Q10. (Safety, Quality Management) How does mechanical index depend on transducer frequency?

- A. Proportional to the square
- B. Inversely proportional to the square
- C. Proportional to the square root
- D. Inversely proportional to the square root

Answer: D – Inversely proportional to the square root

Explanation: Higher frequencies are associated with less chance for tissue cavitation. An increase in frequency from 2 to 8 MHz reduces the MI by the square root of 4. The MI estimates the likelihood of cavitation by ultrasound due to bubble formation. It is directly proportional to the peak rarefactional (negative) pressure and inversely proportional to the square root of the US beam frequency.

References:

1. Abbott, J.G. “Rationale and Derivation of MI and TI: a Review.” *Ultrasound Med. Biol.* 25:431–441, 1999.
2. Houston, L.E., et al. “Ultrasound is safe...right? Resident and maternal-fetal medicine fellow knowledge regarding obstetric ultrasound safety.” *J. Ultrasound Med.* 30:21–7, 2011.
3. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q11: (Underlying Technology and Physics Principles) What is the wavelength of a 1.5 MHz wave?

- A. 1.5 cm
- B. 1.0 cm
- C. 1.5 mm
- D. 1.0 mm
- E. 1.5 μ m

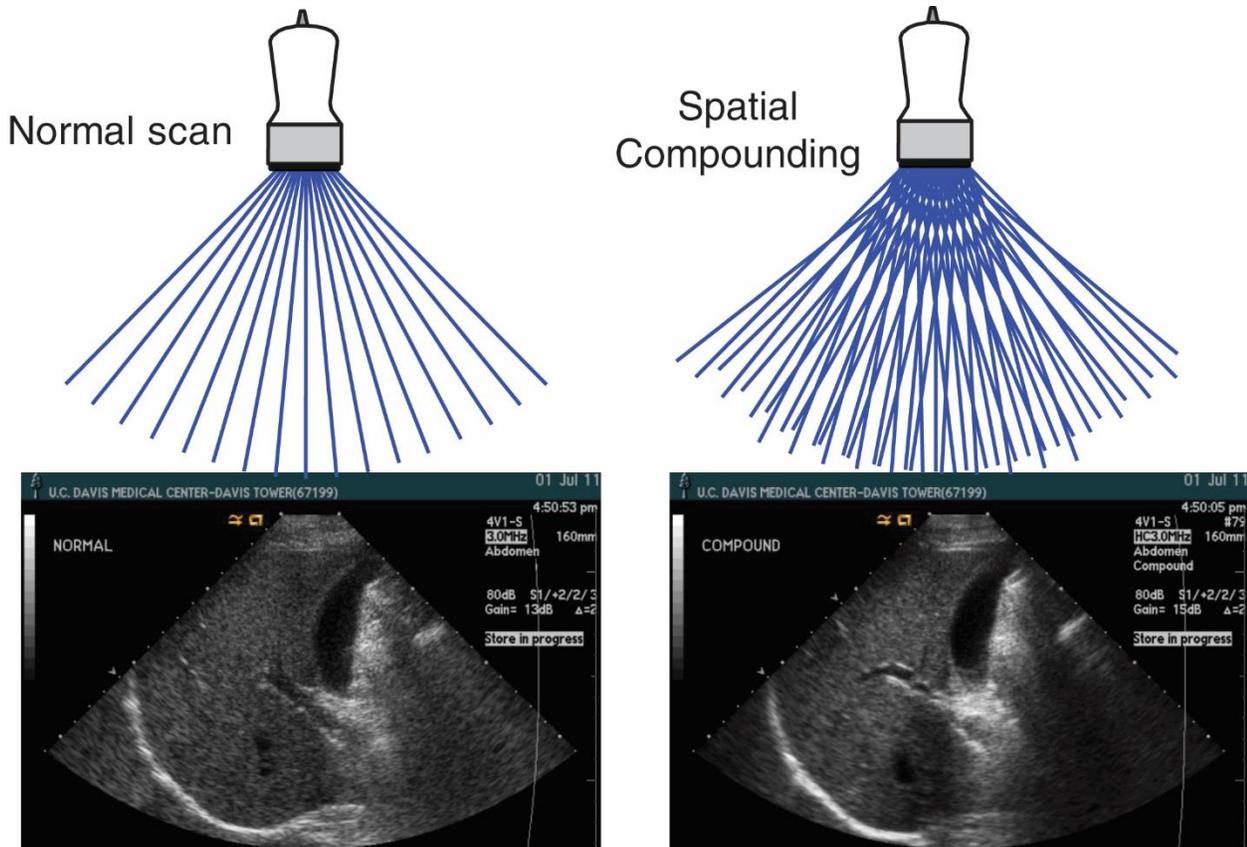
Answer: D – 1.0 mm

Explanation: The speed of sound in soft tissue is roughly 1500 m/s. Since wavelength \times frequency equals speed of sound, the wavelength will be 1.5 MHz divided by 1500 m/s, which gives 1.0 mm. Knowing this is important since wavelength sets limits on resolution and also determines whether a reflection is specular or diffuse.

References:

1. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

- Q12.** (Effective Use) What is a disadvantage of spatial compounding compared to normal scan mode?
- Reduced signal-to-noise ratio
 - Increased spatial blurring of moving objects
 - Increased prominence of speckle noise
 - Reduced depth of penetration



(Image Credit: *Essential Physics of Medical Imaging*, Bushberg et al., 2012.)

Answer B: Increased spatial blurring of moving objects

Explanation: Compound imaging uses ultrasound beams produced at several angles achieved by electronic steering to acquire directional acoustic image data subsequently averaged to produce a single image. There is oversampling in this mode, and since the scan lines are acquired sequentially, the frame rate is reduced by the number of insonation angles used. Speckle noise is reduced by the averaging process. The image obtained has a higher SNR compared to a normal scan. Limitations of compound scanning include persistence of frame averaging effect causing loss of temporal resolution, and an increase in spatial blurring of moving objects. This scanning mode is not particularly useful with patient motion. Applications include breast imaging, thyroid, atherosclerotic plaques, and MSK.

References:

1. Anthony Brinton Wolbarst, *Physics of Radiology*, 2nd ed. Madison, Wisconsin: Medical Physics Publishing, 2005.
2. Stewart C. Bushong, *Radiologic Science for Technologists*, 10th ed. St. Louis: Mosby, 2013.
3. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Module 13: Magnetic Resonance Imaging

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Describe the properties of magnetism and how materials react to and interact with magnetic fields.
2. Describe MR system components and their functions.
3. Describe the physical properties of a material that affect the MR signal and how the signal is created.
4. Compare the basic pulse sequences and how T1, T2, proton density, and T2* tissue contrast can be achieved.
5. Describe how spatial localization of the signal is achieved (gradients).
6. Explain the principles of *k*-space generation and describe how to “fill *k*-space” to optimize signal strength (signal-to-noise ratio) and acquisition time.
7. Explain the basic principles of diffusion, perfusion, and flow imaging.
8. Differentiate between phase-contrast, 2D time-of-flight, and 3D time-of-flight MR angiography.
9. Explain the basic concepts of functional MRI.
10. Describe the types of contrast agents used in MR and how they affect the signal relative to the pulse sequence used.
11. Evaluate how image acquisition parameters impact image quality, tissue contrast, and acquisition time.
12. Understand the safety and bioeffects of concern in MR imaging.

Clinical Applications and Problem Solving:

1. Identify the most appropriate pulse sequences for a specific diagnostic task.
2. Describe risks and benefits of MR contrast agents.
3. Describe the risks and benefits when MR imaging is used on a pregnant patient.
4. Discuss clinical situations in which MRI procedures are contra-indicated.
5. Determine the source of common artifacts and describe methods to mitigate their appearance.
6. Discuss how different field strength systems change the acquisition parameters and image quality in MRI
7. Discuss how MR parameters affect biosafety.

Curriculum:

13. Magnetic Resonance Imaging

13.1. Underlying Technology and Physics Principles

13.1.1. Magnetism and Magnetic Fields [2.9]

13.1.1.1. Magnetic Susceptibility (Diamagnetic, Paramagnetic, Ferromagnetic) [2.7]

13.1.2. Magnetic Fields (B) [3.0]

13.1.2.1. Units for Magnetic Field Strength [3.0]

13.1.2.2. Magnetic Dipole [1.5]

13.1.2.3. Magnetic Moment [1.5]

13.1.2.4. Nuclear Magnetism (Protons and Biologically Relevant Nuclei) [2.2]

- 13.1.3. Magnetic Moment Interaction with an External Field (B_0) [2.7]
 - 13.1.3.1. Alignment (Low-Energy and High-Energy States) [1.4]
 - 13.1.3.2. Precession Frequency [2.7]
 - 13.1.3.3. Larmor Equation and Resonance [3.0]
- 13.1.4. Net Magnetization Due to B_0 [3.0]
 - 13.1.4.1. Equilibrium Magnetization (M_0) [2.8]
 - 13.1.4.2. Longitudinal Magnetization (M_z) [2.9]
 - 13.1.4.3. Transverse Magnetization (M_{xy}) [2.9]
 - 13.1.4.4. Proton Density (Spin-Density) [2.7]
 - 13.1.4.5. Field Strength Dependence [2.7]
- 13.1.5. Nuclear Magnetic Resonance and Excitation [3.0]
 - 13.1.5.1. Radiofrequency (RF) Field (B_1) [3.0]
 - 13.1.5.2. Flip Angle [3.0]
 - 13.1.5.3. Free-Induction Decay (FID) [2.7]
- 13.1.6. Magnetic Resonance Signal Properties [3.0]
 - 13.1.6.1. Proton Density (Spin Density) [2.9]
 - 13.1.6.2. (Transverse) Relaxation [3.0]
 - 13.1.6.2.1. Intrinsic Spin-spin Interactions [2.9]
 - 13.1.6.2.2. Transverse Magnetization Decay [3.0]
 - 13.1.6.2.3. Relative Tissue T2 Values (“Long” vs. “Short”) [3.0]
 - 13.1.6.3. T2* Relaxation [2.8]
 - 13.1.6.3.1. Dependence on Field Inhomogeneity [2.6]
 - 13.1.6.3.2. Susceptibility Induced Dephasing (e.g., Tissue-Air Interfaces) [2.8]
 - 13.1.6.4. T1 (Longitudinal) Relaxation [3.0]
 - 13.1.6.4.1. Spin-lattice Interactions [2.9]
 - 13.1.6.4.2. Longitudinal Recovery [3.0]
 - 13.1.6.4.3. Relative Tissue T1 values (“Long” vs. “Short”) [3.0]
 - 13.1.6.4.4. Field-Strength Dependence [2.7]
- 13.1.7. Pulse Sequences and Contrast Mechanisms [3.0]
 - 13.1.7.1. Pulse Sequence Parameters (TR, TE, Flip Angle, Inversion Time) [3.0]
 - 13.1.7.2. Spin-echo (SE) Pulse Sequence [3.0]
 - 13.1.7.2.1. SE Signal Intensity Dependence on TE and TR [3.0]
 - 13.1.7.2.2. SE Contrast (T1, Proton Density, T2) [3.0]
 - 13.1.7.3. Inversion-Recovery Spin-Echo Pulse Sequence [2.9]
 - 13.1.7.3.1. Short-Tau Inversion-Recovery (STIR) [2.9]
 - 13.1.7.3.2. Fluid-Attenuated Inversion-Recovery (FLAIR) [2.9]
 - 13.1.7.4. Gradient-Echo Pulse Sequence [2.8]
 - 13.1.7.4.1. Types of Gradient-Echo Pulse Sequences (Steady State, Spoiled) [2.8]
 - 13.1.7.4.2. Advantages and Disadvantages [2.7]
 - 13.1.7.4.3. Signal-Intensity and Effect of Flip Angle [2.5]

- 13.1.7.4.4. Spoiling (RF and Gradient) [2.3]
- 13.1.7.4.5. Gradient Echo Contrast (T2*/T1, T2*, and T1 Weighting) [2.6]
- 13.1.7.5. Echo-planar (EPI) [2.7]
 - 13.1.7.5.1. Single-Shot Method [2.5]
 - 13.1.7.5.2. Multi-Shot Method [2.5]
 - 13.1.7.5.3. T2* Contrast [2.9]
- 13.1.7.6. Fast or Turbo Spin-Echo [2.9]
 - 13.1.7.6.1. Echo Train Length and Spacing [2.5]
 - 13.1.7.6.2. Effective TE [2.7]
 - 13.1.7.6.3. Contrast (T2 and T1 Weighting) [2.9]
- 13.1.8. Spatial Localization [3.0]
 - 13.1.8.1. Slice Selection [3.0]
 - 13.1.8.2. Phase Encoding [3.0]
 - 13.1.8.3. Frequency Encoding [2.8]
 - 13.1.8.4. Multi-Slice Acquisition [2.1]
 - 13.1.8.5. 2D and 3D Acquisitions [2.8]
- 13.1.9. Pulse Sequence Timing Diagrams [2.4]
- 13.1.10. Factors that Affect Acquisition Time [2.9]
- 13.1.11. Two-Dimensional Fourier Transform (2DFT) Image Reconstruction [1.9]
 - 13.1.11.1. *k*-Space Description [3.0]
 - 13.1.11.2. Methods of “Filling *k*-Space” [1.9]
- 13.1.12. MR Instrumentation [2.7]
 - 13.1.12.1. Static Magnetic Field (B₀) Systems [2.4]
 - 13.1.12.1.1. Types of Magnets [1.7]
 - 13.1.12.1.2. Fringe Field [2.4]
 - 13.1.12.1.3. Main Magnetic Field Shielding (Fringe Field Reduction) [1.7]
 - 13.1.12.2. Gradient Field Subsystem [1.9]
 - 13.1.12.2.1. Gradient Coil Geometry (X, Y, and Z) [2.0]
 - 13.1.12.2.2. Gradient Strength (mT/m) [2.5]
 - 13.1.12.2.3. Slew-Rate: Specification (mT/m/s), Eddy Currents, and Effects on Gradient Performance [1.9]
 - 13.1.12.2.4. Shim Coils [1.8]
 - 13.1.12.3. RF Transmitter (B₁) Subsystem [1.8]
 - 13.1.12.3.1. RF-pulse Bandwidth [2.6]
 - 13.1.12.3.2. Control of Flip Angle [2.0]
 - 13.1.12.3.3. Multi-Transmit Benefits [1.8]
 - 13.1.12.4. RF Receiver Subsystem [2.0]
 - 13.1.12.4.1. Receive Bandwidth [2.7]
 - 13.1.12.4.2. Parallel (and Phased-Array) Receive Channels [2.5]
 - 13.1.12.5. RF Coils [2.6]
 - 13.1.12.5.1. Transmit-and-Receive vs. Receive-Only Coils [2.7]
 - 13.1.12.5.2. Surface Coils and Phased-Array Coils [2.5]

13.1.12.5.2.1.1. Impact on SNR and Uniformity [2.8]

- 13.2. Effective Use
 - 13.2.1. Paramagnetic and Other Contrast Agents [2.5]
 - 13.2.2. Suppression Methods and Effects [2.5]
 - 13.2.2.1. Spatial [2.7]
 - 13.2.2.2. Chemical (e.g., Fat, Silicone) [2.8]
 - 13.2.2.2.1. Hybrid Sequences (SPIR, SPAIR) [1.9]
 - 13.2.2.3. Inversion Recovery [3.0]
 - 13.2.2.4. Dixon Method and Opposed Phase [2.5]
 - 13.2.3. Special Acquisition Techniques [2.6]
 - 13.2.3.1. Angiography [2.8]
 - 13.2.3.1.1. Effect of Blood Flow on Signal Intensity [2.8]
 - 13.2.3.1.2. Time-of-Flight (2D and 3D) Techniques [2.9]
 - 13.2.3.1.3. Phase-Contrast Techniques [2.7]
 - 13.2.3.1.4. Flow Compensation vs. Spatial Saturation [1.6]
 - 13.2.3.1.5. Contrast Enhanced MRA [2.3]
 - 13.2.3.1.6. Magnetization Transfer [1.9]
 - 13.2.3.2. Diffusion and Perfusion [2.7]
 - 13.2.3.2.1. Diffusion-Weighted Imaging (DWI) [2.6]
 - 13.2.3.2.2. Apparent Diffusion Coefficient (ADC) [2.3]
 - 13.2.3.2.3. Diffusion-Tensor Imaging (DTI) [2.2]
 - 13.2.3.2.4. Dynamic Susceptibility Contrast Perfusion (T2*) [2.2]
 - 13.2.3.3. Parallel Imaging MRI (Acceleration and SNR) [2.3]
 - 13.2.3.4. Cardiac Imaging [2.0]
 - 13.2.3.5. Susceptibility Weighted Imaging (SWI) [2.2]
 - 13.2.3.6. Breast MRI [2.3]
- 13.3. Image Characteristics and Artifacts
 - 13.3.1. Factors Affecting Spatial Resolution [3.0]
 - 13.3.1.1. Field-of-View (FOV) [3.0]
 - 13.3.1.2. Receiver (Sampling) Bandwidth [3.0]
 - 13.3.1.3. Slice Thickness [3.0]
 - 13.3.1.4. Image Matrix Dimensions [3.0]
 - 13.3.2. Factors Affecting Signal-to-Noise Ratio (SNR) [3.0]
 - 13.3.2.1. Voxel Size [3.0]
 - 13.3.2.2. Signal Averages [3.0]
 - 13.3.2.3. Receiver (Sampling) Bandwidth [3.0]
 - 13.3.2.4. Magnetic Field Strength [3.0]
 - 13.3.2.5. Slice “Cross-talk” [2.3]
 - 13.3.2.6. Reconstruction Algorithms [2.3]
 - 13.3.2.7. RF Coils [2.4]
 - 13.3.2.8. Pulse Sequence Specific Effects [2.4]
 - 13.3.2.9. Parallel Imaging Acceleration Factors [2.3]

- 13.3.2.10. Saturation and Flow [2.6]
- 13.3.2.11. 3D vs. 2D [2.5]
- 13.3.3. Tradeoffs among Spatial Resolution, SNR, and Acquisition Time [3.0]
- 13.3.4. Factors Affecting Image Contrast [2.9]
 - 13.3.4.1. Proton Density, T1, T2 [2.9]
 - 13.3.4.2. Susceptibility [2.8]
 - 13.3.4.3. Blood Flow and Blood Products [2.8]
 - 13.3.4.4. Contrast Media [2.9]
- 13.3.5. Artifacts
 - 13.3.5.1. Patient-Based (Motion, etc.) [3.0]
 - 13.3.5.2. *k*-Space (Spike, etc.) [2.7]
 - 13.3.5.3. Equipment-based (Inhomogeneity, etc.) [3.0]
 - 13.3.5.4. Acquisition Parameter-Based (Gibbs Ringing, etc.) [3.0]
 - 13.3.5.5. High-speed Imaging Artifacts (e.g., Echo-planar Distortion, etc.) [2.6]
 - 13.3.5.6. Parallel Imaging Artifacts [2.2]
 - 13.3.5.7. Flow-Related Artifacts [2.5]
- 13.4. Safety, Quality Management, and Regulatory Issues
 - 13.4.1. Safety and Bioeffects [3.0]
 - 13.4.1.1. Static Magnetic Field, Fringe Field, and Spatial Gradients Fields [3.0]
 - 13.4.1.1.1. Projectile Hazards [3.0]
 - 13.4.1.1.2. Effects on Implanted Devices [3.0]
 - 13.4.1.1.3. FDA Limits [2.7]
 - 13.4.1.2. RF Field [3.0]
 - 13.4.1.2.1. Biological Effects (e.g., Tissue Heating and Other) [3.0]
 - 13.4.1.2.2. RF Heating of Conductors and Potential Burns [3.0]
 - 13.4.1.2.3. Specific Absorption Rate (SAR) [2.8]
 - 13.4.1.2.4. Root mean square RF transmit (B1+rms) and Specific Energy Dose (SED) [1.8]
 - 13.4.1.2.5. High Field Strength System Issues [1.6]
 - 13.4.1.2.6. FDA Limits [2.4]
 - 13.4.1.2.7. Reducing RF Heating Effects [2.7]
 - 13.4.1.3. Gradient Field [2.2]
 - 13.4.1.3.1. Biological Effects, Including Peripheral Nerve Stimulation [2.4]
 - 13.4.1.3.2. Sound Pressure Level (“Noise”) Issues [2.1]
 - 13.4.1.3.3. FDA Limits [2.0]
 - 13.4.1.4. Gadolinium-Based Contrast Agents
 - 13.4.1.4.1. Nephrogenic Systemic Fibrosis
 - 13.4.2. Applied MRI Safety
 - 13.4.2.1. Screening Patients and Healthcare Workers [2.9]
 - 13.4.2.2. MR Safety Systems and Superconducting Magnet “Quench” Systems [2.7]
 - 13.4.2.3. Current Risk vs. Benefit Guidance for Pregnant Patients and Staff [2.5]

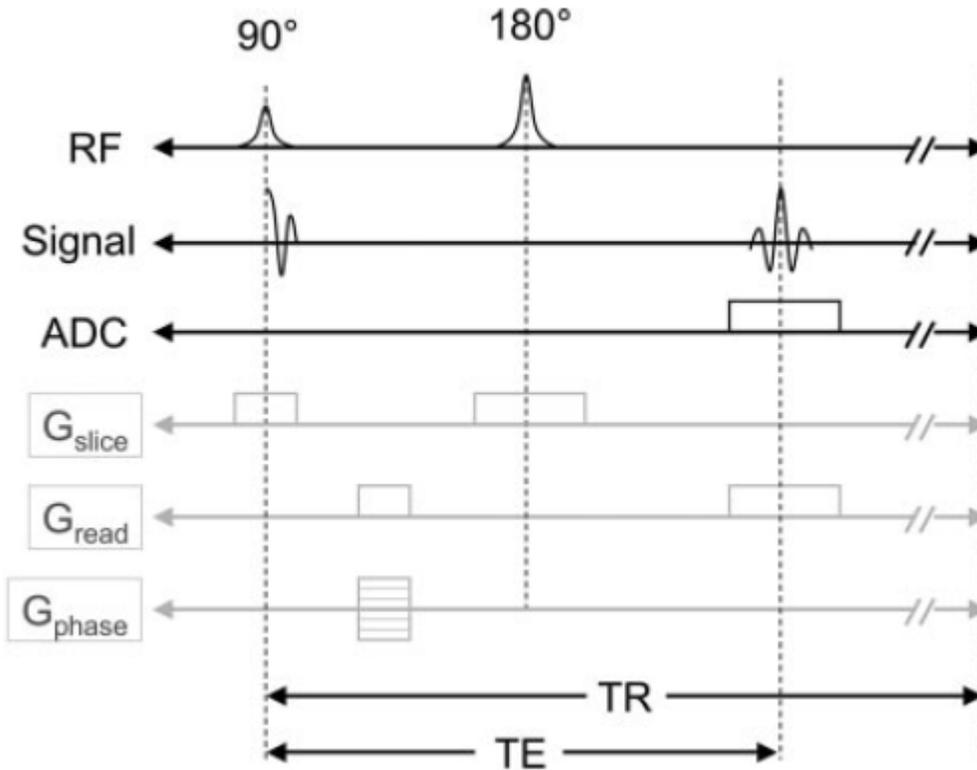
- 13.4.2.4. MR Safety Labeling [2.8]
- 13.4.2.5. ACR, The Joint Commission, and the MR Safety Committee [2.5]
- 13.4.2.6. Magnet System Siting [1.8]
 - 13.4.2.6.1. Safety Zones [2.9]
 - 13.4.2.6.2. Magnetic Fringe Field and the 0.5 mT (5G) Line [2.6]
 - 13.4.2.6.3. Magnetic and RF Field Shielding [1.6]
- 13.4.2.7. ACR/TJC Accreditation and Quality Improvement [2.0]
 - 13.4.2.7.1. MR Quality Assurance Committee [1.4]

13.5 Modality-Specific References:

1. Expert Panel on MR Safety. ACR Guidance Document on MR Safe Practices: *J. Magn. Reson. Imaging* 37:501–530, 2013.
2. www.mrisafety.com run by Institute For Magnetic Resonance Safety, Education, and Research.
3. Hashemi, R.H., Bradley, W.G., Lisanti, C.J. *MRI: The Basics*. Lippincott, Williams and Wilkens, 2010.
4. McRobbie, D.W., et al. *MRI from Proton to Picture*. Cambridge University Press, 2017.

Example Q&A:

Q1. (Underlying Technology and Physical Principles) What MR pulse sequence timing diagram is illustrated in the figure below?



(Image from Pooley, R.A. "Fundamental Physics of MR Imaging." *Radiographics* 25(4):1087–1099, 2005.)

- A. Gradient echo (GRE) sequence
- B. Fast spin echo (FSE) sequence
- C. Echo Planar Imaging (EPI) sequence
- D. Spin echo (SE) sequence

Answer: D – Spin echo (SE) sequence

Explanation: A spin echo sequence uses one 90° RF pulse to excite spins and one 180° RF pulse to refocus the spins to generate signal via spin echoes. A fast spin echo sequence uses one 90° RF pulse and multiple refocusing RF pulses (traditionally, 180°). A gradient echo does not use any 180° RF pulses. An echo planar imaging sequence contains multiple gradient echoes within one TR.

References:

1. Runge, V.M., W.R. Nitz, and S.H. Schmeets. *The Physics of Clinical MR Taught Through Images*, 2nd ed. New York: Thieme, 2008.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2011.

Q2. (Underlying Technology and Physical Principles) How does scan time change if ETL is increased from 1 to 4?

- A. Quartered
- B. Halved
- C. Doubled
- D. Quadrupled

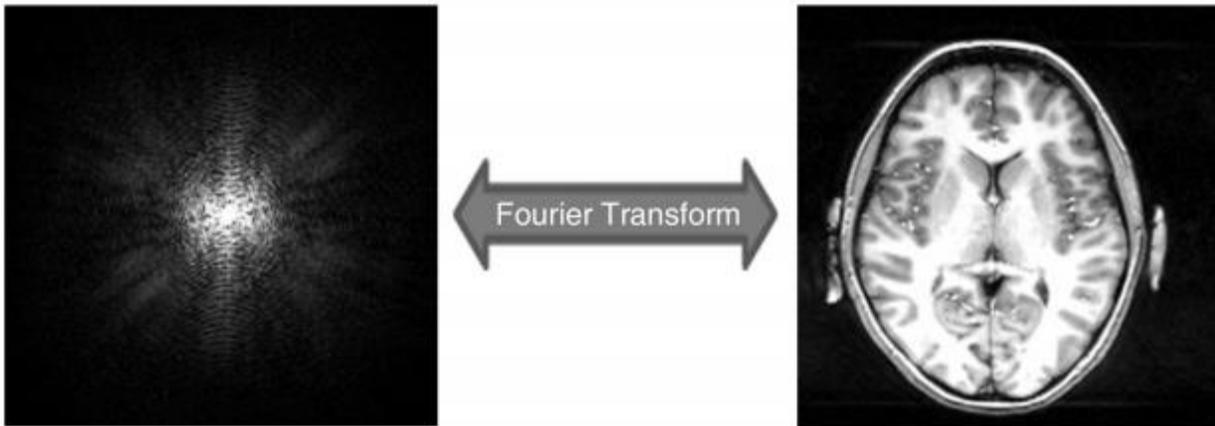
Answer: A – Quartered

Explanation: Acquisition time reduction is inversely proportional to echo train length for an FSE sequence compared to conventional SE sequence. For example, an echo train of four reduces acquisition time by a factor of four. That means the k -space can be filled four times faster than the SE sequence.

References:

1. Runge, V.M., W.R. Nitz, and S.H. Schmeets. *The Physics of Clinical MR Taught Through Images*, 2nd ed. New York: Thieme, 2008.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2011.

Q3. (Underlying Technology and Physical Principles) Which part of the k -space determines the image sharpness?



(Image from Qureshi, M. “Journey through k -space: an interactive educational tool.” *Biomed Res-India* 28(4):1618–1623, 2017.)

- A. Center of k -space
- B. Peripheral part of k -space
- C. Left half of the k -space
- D. Right half of the k -space

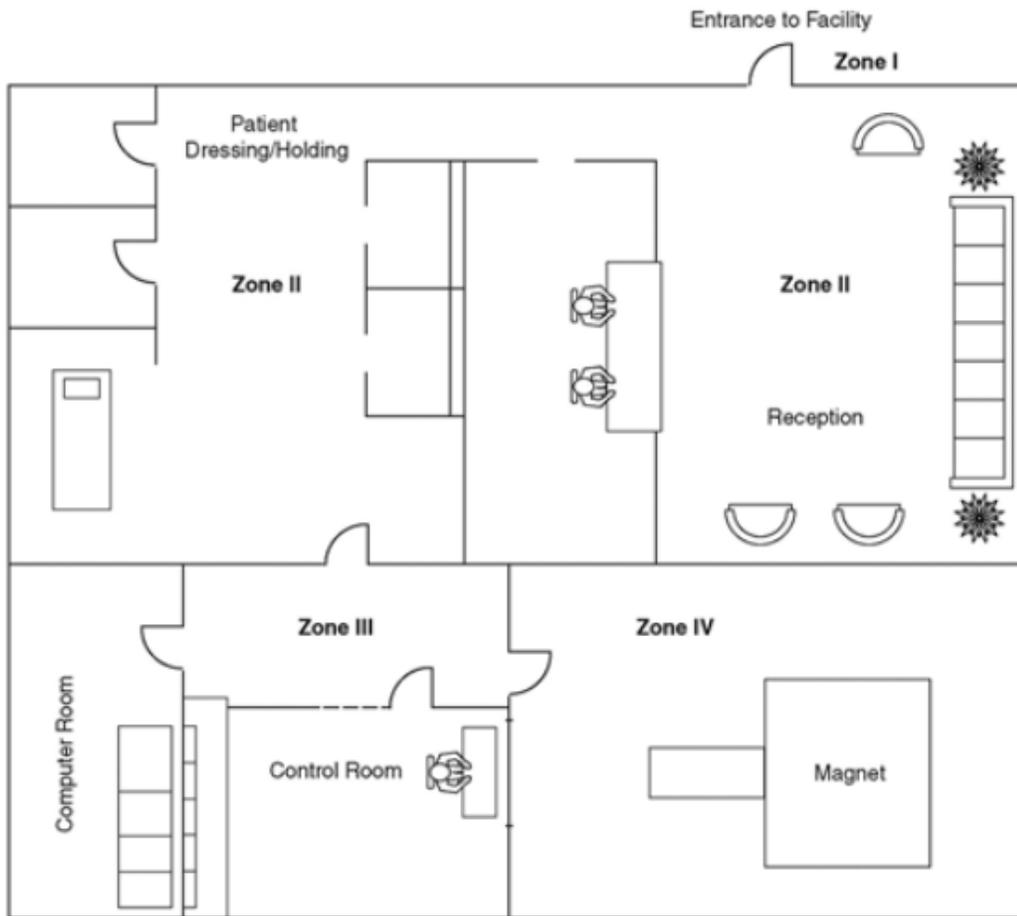
Answer: B – Peripheral part of the k -space

Explanation: MR signal is acquired in the frequency domain (time domain) and stored in a k -space matrix. Its inverse Fourier Transform generates the image. The center of the k -space controls the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR). The periphery of k -space contributes to the high-frequency detail of the image.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2011.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q4. (Safety, Quality Management, and Regulatory Issues) According to ACR guidelines, who is allowed unrestricted access to Zone III as shown in the following map?



(Image from Kanal, et al. “ACR Guidance Document for Safe MR Practices: 2007.” *Am. J. Roentgenol.* 188(6):1447–1474, 2007.)

- A. Level 1 MR personnel only
- B. Level 2 MR personnel only
- C. Both Level 1 and Level 2 MR personnel
- D. Neither Level 1 or level 2 MR personnel

Answer: C – Both Level 1 and level 2 MR personnel

Explanation: Level 1 MR personnel have passed minimal safety and education training on MR safety issues. Level 2 MR personnel have had extensive MR safety training within the last 12 months. Typically Level 2 personnel include MR technologists, MR radiologists, MR physicists, and MR service engineers. Both Level 1 and Level 2 MR personnel are allowed free access to Zone III.

Reference:

Kanal, et al. “ACR Guidance Document on MR Safe Practices: 2013.” *J. Magn. Reson. Imaging* 37(3):501–30, 2013.

Q5. (Safety, Quality Management, and Regulatory Issues) What is the most commonly reported adverse event associated with MRI?

- A. Missile events
- B. Implant movement
- C. Thermal injuries
- D. Hearing loss

Answer: C – Thermal injuries

Explanation: In a recent review of the U.S. FDA’s Manufacturer and User Facility Device Experience Database (MAUDE), Hardy and Weil found reports of 419 thermal injuries associated with MRI over a period of 10 years.

Reference:

- 1) <http://www.fda.gov/MedicalDevices/DeviceRegulationandGuidance/PostmarketRequirements/ReportingAdverseEvents/ucm127891.htm>.
- 2) Hardy, P.T., Weil, K.M. “A review of thermal MR injuries.” *Radiol Technol* 81:606–9, 2010.

Q6. (Safety, Quality Management, and Regulatory Issues) According to the ACR safe practice guidelines, can a patient with an MR conditional pacemaker be scanned?

- A. Yes, the pacemaker can be safely scanned under any conditions (e.g., field strength, SAR)
- B. Yes, the pacemaker may be safely scanned under specific conditions (e.g., field strength, SAR)
- C. No, the pacemaker cannot be safely scanned, and the patient should be referred for other imaging.
- D. Undetermined. There is not enough information to determine if the patient can be scanned safely.

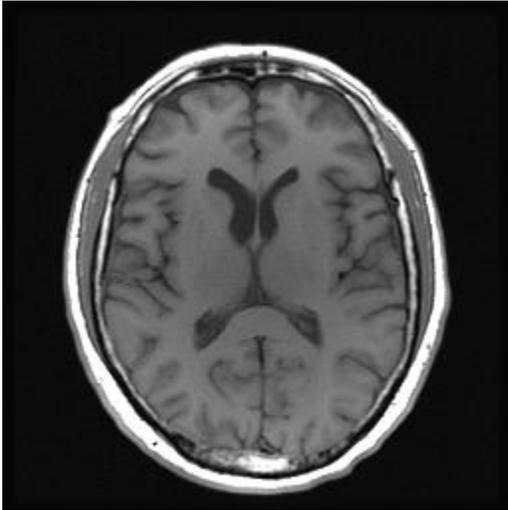
Answer: B – Yes, the pacemaker may be safely scanned under specific conditions (e.g., field strength, SAR).

Explanation: While some modern pacemakers are commonly referred to as “MR Safe,” none have been shown to function safely under all clinical scanning conditions. However, MR conditional pacemakers can be scanned following specific guidelines usually put out by the manufacturer.

Reference:

Kanal, et al. “ACR Guidance Document on MR Safe Practices: 2013.” *J. Magn. Reson. Imaging* 37(3):501–30, 2013.

Q7. (Effective Use) What combination of TE and TR times is used to generate a spin-echo T1-weighted image of the brain?



(Image courtesy of Ping Hou)

- A. Short TR, Short TE
- B. Long TR, Long TE
- C. Short TR, Long TE
- D. Long TR, Short TE

Answer: A – Short TR, Short TE

Explanation: For the spin echo sequence, TR primarily controls the amount of T1-weighting, whereas TE primarily controls the amount of T2-weighting. Therefore, a relatively short TR and very short TE should be used (so that the T2 effect can be minimized) to generate T1W image. Long TR and long TE generate T2-weighted image. Long TR and short TE generate proton density image.

References:

1. Runge, V.M, W.R. Nitz, and S.H. Schmeets. *The Physics of Clinical MR Taught Through Images*, 2nd ed. New York: Thieme, 2008.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q8. What method of fat suppression results in the greatest reduction in fat signal for a patient with an MR safe metal implant?

- A. Spectral selective fat suppression
- B. STIR technique
- C. Saturation Band
- D. DIXON method

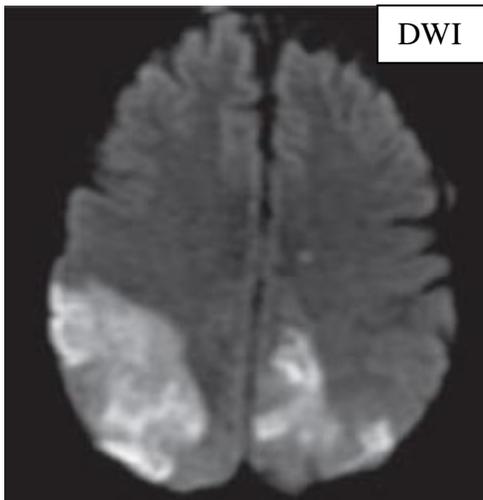
Answer: B – STIR technique

Explanation: Spectral selective fat suppression is sensitive to the main magnetic field inhomogeneity which is prominent in the presence of metallic implants. STIR stands for Short Tau Inversion Recovery. The inversion time TI (short tau) in a STIR sequence is chosen to null the signal from fat based upon its T1 recovery time ($TI = \ln 2 * T1$). Fat T1 is generally uniform and relatively independent of small differences in magnetic field inhomogeneity. As a result, STIR sequences are quite robust in tissue regions that have metallic/tissue interfaces. STIR should not be used for post contrast fat suppression, since gadolinium-containing tissues with similar T1s will also be suppressed. T2W image does not suppress fat at all. DIXON is a method based on opposed-phase experienced by water and fat. Two or more echoes have to be acquired to generate in- and out-phase images; from them a pure water and fat images can be reconstructed. It is still susceptible to static field inhomogeneity. Another issue for DIXON is phase/intensity swap of water and fat, prone to the quick variation area at the implant area. A saturation band is a spatially localized rectangular area of tissue that is selected by the technologist to give no signal. This is typically used to negate motion artifacts from breathing or swallowing or remove either veins or arteries from an MRA.

References:

1. Runge, V.M, W.R. Nitz, and S.H. Schmeets. *The Physics of Clinical MR Taught Through Images*, 2nd ed. New York: Thieme, 2008.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
3. Dixon, W.T. "Simple proton spectroscopic imaging." *Radiology* 153:189–194, 1984.

Q9. (Effective Use) What type of image, when combined with diffusion weighting, would generate contrast in a diffusion-weighted image?



(Image from Bitar, R., et al. “MR Pulse Sequences: What Every Radiologist Wants to Know but Is Afraid to Ask.” *Radiographics* 26(2):513–537, 2006.

- A. T1 weighting
- B. T2 weighting
- C. T2/T1 weighting
- D. Proton density weighting

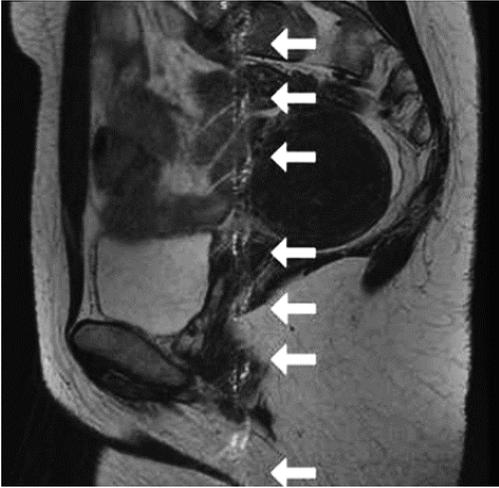
Answer: B – T2 weighting.

Explanation: Usually, diffusion-weighted images are generated using spin echo-based (SE) echo planner imaging (EPI) sequence. Strong diffusion gradients are inserted before and after the 180 RF pulses which will typically extend the echo time to 60 to 100 msec, depending upon gradient performance. Therefore, diffusion-weighted images have significant T2 weighting resulting from the long echo time. The ADC map is created in an attempt to eliminate the T2 weighting, leaving image contrast based only on the apparent diffusion (no T2 shine through) coefficient.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Runge, V.M, W.R. Nitz, and S.H. Schmeets. *The Physics of Clinical MR Taught Through Images*, 2nd ed. New York: Thieme, 2008.

Q10. (Artifacts) What is the most likely explanation for the ribbon (ghost) artifact observed when using a fast spin echo sequence with a multi-channel body array coil? (Note: phase encoding direction is aligned along the superior–inferior (SI) direction.)



(Image reference: Graves, M.J. and Mitchell, D.G. “Body MRI artifacts in clinical practice: A physicist’s and radiologist’s perspective. *J. Magn. Reson. Imaging* 38:269–287, 2013.

- A. Motion artifacts
- B. RF interference from the environment
- C. Peripheral signal artifacts
- D. Bad RF coil

Answer: C – Peripheral signal artifacts

Explanation: It is not motion artifacts (choice A), since there is no anatomic replicate in the phase encoding direction. If it were RF interference (choice B) from the environment, the zipper or ghost would extend in the frequency-encoding direction and would not change position from slice to slice. If it was a bad RF coil (choice D) then we would expect some shading at the same location for each slice, but there is no SNR drop at all.

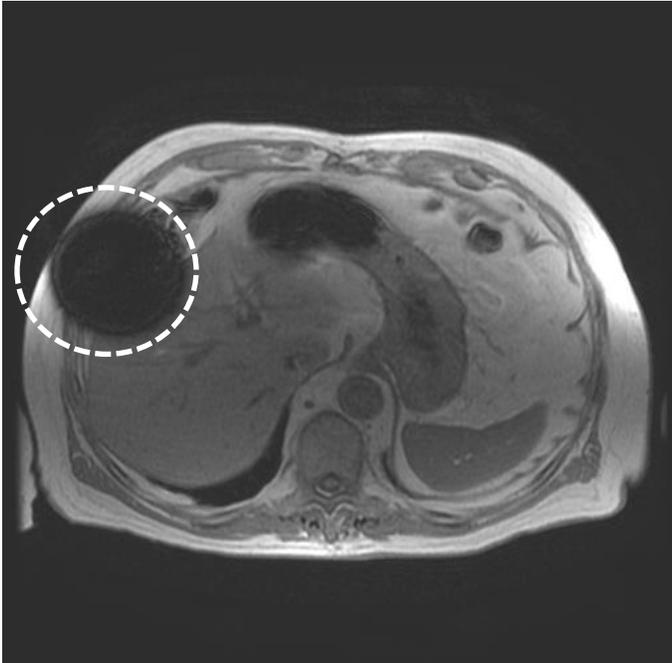
Peripheral signal artifacts appear as either bright spots or as ribbons (ghost) of signal smeared through the image in the phase-encoding direction. We refer to these artifacts as Star artifacts (bright spot) or Anefacts (ribbons). It is all due to anatomy within the active volume of the coil, but outside the FOV and the receivers can detect them.

This happens more with multi-channel coil when the FOV is located close to the edge of (lower part of the coil in this case) coil, especially when saturation RF applied. The artifacts could have been prevented/reduced by (1) keeping the image FOV far from the edge of the sensitive region of the receive coil; (2) swapping the phase encoding direction; (3) removing the spatial saturation RF pulse.

References:

1. MR Field notes, GE health care.
http://www.gehealthcare.com/us/en/education/tip_app/docs/fieldnotes_volume1-2_coils.pdf .
2. Zhuo, J. and R.P. Gullapalli. “AAPM/RSNA Physics Tutorial for Residents, MR Artifacts, Safety and Quality Control.” *RadioGraphics* 26:275–297, 2006.
<http://pubs.rsna.org/doi/full/10.1148/rg.261055134>

Q11. (Artifacts) How would you mitigate the artifact shown on this gradient echo image?



(Image courtesy of Ping Hou.)

- A. Use flow suppression
- B. Use a spin echo sequence
- C. Increase TE
- D. Increase TR

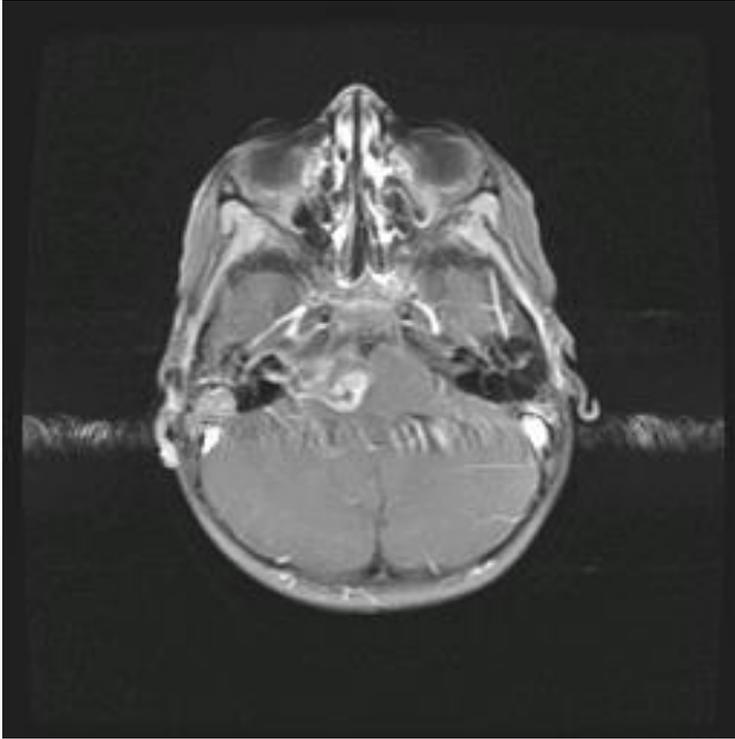
Answer: B – Use a spin echo sequence

Explanation: This is a clinical abdomen image showing a susceptibility artifact from a metal implant. Magnetic susceptibility of metal differs from that of surrounding tissue, causing large local magnetic field change (inhomogeneity). This large field inhomogeneity results in rapid phase dephasing and, therefore, signal loss. The 180-degree RF pulse in the spin echo sequence reverses spin dephasing due to field inhomogeneities; the gradient echo sequence only reverses spin dephasing caused by the gradient itself. Therefore, SE is less sensitive to magnetic susceptibility. Decreased TE in gradient echo could reduce this kind of artifact as well.

References:

1. Elster, A.D. and J.H. Burdette. *Questions and Answers in Magnetic Resonance Imaging*, 2nd ed. St. Louis: Mosby, 2001.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
3. Zhuo, J. and R.P. Gullapalli. “AAPM/RSNA Physics Tutorial for Residents, MR Artifacts, Safety and Quality Control.” *RadioGraphics* 26:275–297, 2006.
<http://pubs.rsna.org/doi/full/10.1148/rg.261055134>.

Q12. (Artifacts) What artifact is present in the image below?



(Image courtesy of Ping Hou)

- A. Patient motion
- B. Flow
- C. RF interference
- D. Gradient failure

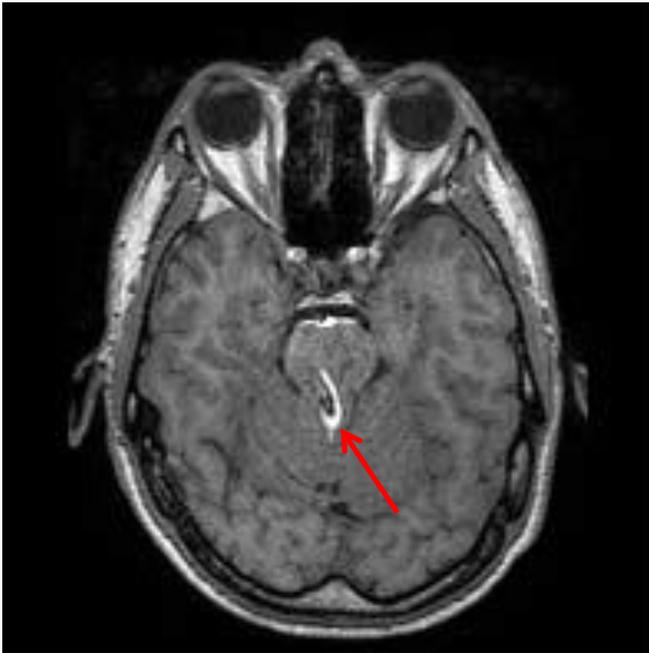
Answer: B – Flow artifact

Explanation: This is a T1W post-contrast brain MR image. Flow artifact is seen close to the vessel in the phase-encoding direction. It is definitely not gradient failure. It is not motion artifact, since ghosting artifacts from motion will present all over the brain in the phase-encoding direction, such as eye movement, head motion, etc. It is not RF interference as well, since the artifact is right next to the vessel. Flow compensation usually can reduce flow artifact. Sometimes SAT pulse could be applied in the neck to suppress carotid arterial flow, too.

References:

1. Edelman, R.R, J.R. Hesselink, M.B. Zlatkin, and J.V. Crues, eds. *Clinical Magnetic Resonance Imaging*, 3rd ed., v1. Philadelphia: Saunders Elsevier, 2006.
2. Zhuo, J. and R.P. Gullapalli. “AAPM/RSNA Physics Tutorial for Residents, MR Artifacts, Safety and Quality Control.” *RadioGraphics* 26:275–297, 2006.
<http://pubs.rsna.org/doi/full/10.1148/rg.261055134>
3. Arena, L., H. Morehouse, and J. Safir. “MR Imaging Artifacts that Simulate Disease: How to Recognize and Eliminate Them.” *Radiographics* 15:1373–1394, 1995.
<http://pubs.rsna.org/doi/pdf/10.1148/radiographics.15.6.8577963>

Q13. (Artifacts) What artifact is indicated with the arrow in this axial multi-planar reconstruction image from a sagittally-acquired 3D brain scan with parallel imaging acceleration?



(Image courtesy of Trevor Andrews)

- A. Flow artifact
- B. Gibbs ringing
- C. RF interference
- D. Aliasing

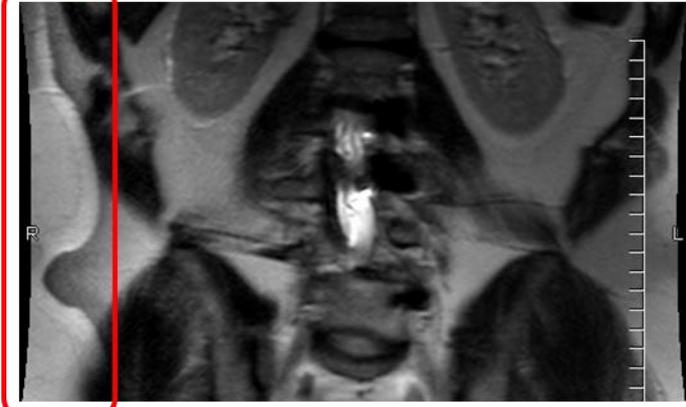
Answer: D – Aliasing

Explanation: The edge of the image shows that the ear was not covered completely and was, therefore, aliased. A flow artifact would cover anatomy with fluid (e.g., blood vessel, ventricle). The most prominent part of a Gibbs ringing artifact would be near a high-contrast edge and would follow the contour of that edge. An RF interference artifact would not be focal.

References:

1. Zhuo, J. and R.P. Gullapalli. “AAPM/RSNA Physics Tutorial for Residents, MR Artifacts, Safety and Quality Control.” *RadioGraphics* 26:275–297, 2006.
<http://pubs.rsna.org/doi/full/10.1148/rg.261055134>
2. Arena, L., H. Morehouse, and J. Safir. “MR Imaging Artifacts that Simulate Disease: How to Recognize and Eliminate Them.” *Radiographics* 15:1373–1394, 1995.
<http://pubs.rsna.org/doi/pdf/10.1148/radiographics.15.6.8577963>

Q14. (Artifacts) How would you correct the following aliasing artifact?



(Image courtesy of Trevor Andrews)

- A. Increase TR
- B. Decrease TE
- C. Decrease NEX
- D. Increase FOV

Answer: D – Increase FOV

Explanation: Aliasing artifacts happen because the size of the object is larger than the FOV. It is a consequence of Nyquist theory: the sampling rate must be at least twice the highest frequency expected, $f_{\text{aliased}} = f_{\text{true}} - 2f_{\text{Nyquist}}$. This could happen in frequency and phase direction, but it is often seen in the phase-encoding direction because in frequency direction, this is avoided by increasing the sampling and using high-pass filters. Using larger FOV will remove aliasing at the cost of spatial resolution. Increasing TR or decreasing TE would change the contrast but not remove the artifact. Decreasing NEX will reduce SNR, but not impact this artifact.

References:

1. Arena, L., H. Morehouse, and J. Safir. “MR Imaging Artifacts that Simulate Disease: How to Recognize and Eliminate Them.” *Radiographics* 15:1373–1394, 1995.
<http://pubs.rsna.org/doi/pdf/10.1148/radiographics.15.6.8577963>
2. Elster, A.D. and J.H. Burdette. *Questions and Answers in Magnetic Resonance Imaging*, 2nd ed. St. Louis: Mosby, 2001.
3. Edelman, R.R., J.R. Hesselink, M.B. Zlatkin, and J.V. Crues, eds. *Clinical Magnetic Resonance Imaging*, 3rd ed., v1. Philadelphia: Saunders Elsevier, 2006.

Module 14: Nuclear Medicine

After completing this module, the resident should be able to apply the “Fundamental Knowledge” learned from the module to example tasks found in “Clinical Applications and Problem-Solving.” Explanation of the priority score listed in brackets in the Curriculum may be found in the Preface.

Fundamental Knowledge:

1. Describe the modes of radioactive decay and resulting emissions.
2. Describe the major components and principles of operation of gamma cameras and positron emission tomography (PET) scanners.
3. Describe the basic operation of instruments commonly used for measuring and calibrating radioactivity.
4. Describe key instrumentation quality control (QC) tests in nuclear medicine.
5. Describe methods of radionuclide production, including the theory of generator-produced radionuclides and quality control tests.
6. Identify common radionuclides and their characteristics, such as energy, half-life, and modes of decay.
7. Identify uptake mechanisms of commonly used radiopharmaceuticals.
8. Describe the methods of determining organ dose and whole body dose to patients.
9. Describe radiopharmaceutical bio-distribution and the impact on radiation dose and risk.
10. Describe the required radiation protection practices for implementing laboratory tests, diagnostic imaging procedures, and therapeutic applications of radiopharmaceuticals.
11. Understand Nuclear Regulatory Commission (NRC)/Agreement State regulations related to nuclear medicine.

Clinical Application and Problem Solving:

1. Compare ideal characteristics of imaging versus therapeutic radiopharmaceuticals.
2. Determine the indications and radiopharmaceutical activity administered to adults and pediatric patients for various imaging procedures.
3. Describe common nuclear medicine image artifacts and the methods to minimize them.
4. Describe how the selection of image acquisition parameters, including collimator selection, affects image quality in planar and SPECT nuclear medicine imaging.
5. Discuss the benefits of time of flight PET.
6. Discuss the factors that limit spatial resolution in PET imaging.

Curriculum:

14. Nuclear Medicine and Positron Emission Tomography (PET)
 - 14.1. Underlying Technology and Physical Principles
 - 14.1.1. Radionuclide Decay [3.0]
 - 14.1.1.1. Nuclear Transformation [3.0]
 - 14.1.1.1.1. N/Z Ratio and Nuclear Stability [3.0]
 - 14.1.1.1.2. Beta (Negative Electron) Decay [3.0]
 - 14.1.1.1.3. Positron (Positive Electron) Decay [3.0]
 - 14.1.1.1.4. Electron Capture [2.9]
 - 14.1.1.1.5. Isomeric Transition [2.9]
 - 14.1.1.1.6. Alpha Decay [2.9]
 - 14.1.1.1.7. Gamma and Internal Conversion [2.9]
 - 14.1.1.1.8. Decay Modes of Commonly Used Radionuclides [3.0]
 - 14.1.1.2. Radioactive Equilibrium [2.3]

- 14.1.1.2.1. Transient and Secular [2.4]
- 14.1.2. Radioactivity [3.0]
 - 14.1.2.1. Definition of Radioactivity [3.0]
 - 14.1.2.2. Units [3.0]
 - 14.1.2.3. Decay Constant and Decay Rate [3.0]
 - 14.1.2.4. Decay Equation [3.0]
 - 14.1.2.5. Half-life (Physical, Biological and Effective) [3.0]
- 14.1.3. Specific Radioisotope Production [1.6]
 - 14.1.3.1. Reactor [1.6]
 - 14.1.3.1.1. Fission Products [1.6]
 - 14.1.3.1.2. Neutron-Activation Products [1.5]
 - 14.1.3.1.3. Molybdenum Production Process [2.6]
 - 14.1.3.2. Cyclotron [2.4]
 - 14.1.3.2.1. Principle of Operation [1.4]
 - 14.1.3.2.2. Positron Emitting Isotopes [2.9]
 - 14.1.3.3. Radionuclide Generators [2.8]
 - 14.1.3.3.1. $^{99}\text{Mo} - ^{99\text{m}}\text{Tc}$ [2.6]
 - 14.1.3.3.2. Other (e.g., $^{82}\text{Sr} - ^{82\text{Rb}}$ PET) [2.3]
 - 14.1.3.3.3. Elution and Quality Control [2.6]
- 14.1.4. Radiopharmaceuticals [2.6]
 - 14.1.4.1. Preparation [2.4]
 - 14.1.4.2. Diagnostic Reference Levels for Clinical Studies [2.3]
 - 14.1.4.3. Uptake, Distribution, and Clearance Kinetics [1.6]
 - 14.1.4.4. Quality Assurance and Quality Control Procedures [2.4]
 - 14.1.4.5. Specific Activity [2.6]
- 14.1.5. Tracer Concept [2.6]
- 14.1.6. Scintillation Camera [3.0]
 - 14.1.6.1. Clinical Utilization [2.9]
 - 14.1.6.2. Camera Design [3.0]
 - 14.1.6.2.1. Crystal Parameters [3.0]
 - 14.1.6.2.2. Spatial Localization, Anger camera principles [2.9]
 - 14.1.6.2.3. Energy Discrimination [3.0]
 - 14.1.6.2.4. Camera Corrections [3.0]
 - 14.1.6.3. Collimator Types and Characteristics [3.0]
 - 14.1.6.3.1. Parallel Hole, Pinhole, and Other Geometries [3.0]
 - 14.1.6.3.2. Sensitivity [3.0]
 - 14.1.6.3.3. Resolution [3.0]
 - 14.1.6.3.4. Energy Specification (e.g., LEHR, ME, HE) [3.0]
 - 14.1.6.4. Image Acquisition [2.9]
 - 14.1.6.4.1. Static [2.9]
 - 14.1.6.4.2. Dynamic [2.9]
 - 14.1.6.4.3. Gated [2.9]
 - 14.1.6.4.4. List-Mode [2.3]
 - 14.1.6.4.5. Matrix Size (e.g. Zoom) [3.0]
 - 14.1.6.4.6. Count Rate and Administered Activity Considerations [2.8]
 - 14.1.6.5. Image Processing [2.6]
 - 14.1.6.5.1. Normalization and Subtraction [2.4]
 - 14.1.6.5.2. Region of Interest (ROI) [2.4]

- 14.1.6.5.3. Time–Activity Curves [2.6]
 - 14.1.6.5.4. Spatial Filtering [2.4]
 - 14.1.6.6. Gamma Camera Quality Control (Extrinsic and Intrinsic) [2.8]
 - 14.1.6.6.1. Uniformity [2.8]
 - 14.1.6.6.2. Spatial Resolution [2.8]
 - 14.1.6.6.3. Energy Resolution [2.8]
 - 14.1.6.6.4. Spatial Linearity [2.8]
 - 14.1.6.6.5. Sensitivity [2.8]
 - 14.1.6.6.6. Count-Rate Performance [2.8]
 - 14.1.6.6.7. Dead-Time [2.4]
 - 14.1.7. PET Scanners [3.0]
 - 14.1.7.1. Detector Materials [2.8]
 - 14.1.7.2. Detector Configuration (e.g., Blocks, Rings, 2D/3D, etc.) [2.5]
 - 14.1.7.3. Coincidence Detection [2.9]
 - 14.1.7.3.1. Lines of Response (LOR) [2.9]
 - 14.1.7.3.2. Trues, Scatter, and Random Coincidence Events [2.9]
 - 14.1.7.3.3. Time-of-Flight [2.9]
 - 14.1.8. Cardiac and Respiratory Gating [2.0]
 - 14.1.9. Attenuation Correction [3.0]
 - 14.1.9.1. Computed Tomography [3.0]
 - 14.1.9.2. Mathematical Corrections (e.g., Chang’s Correction) [2.3]
 - 14.1.10. Image Reconstruction and Filtering [2.9]
 - 14.1.10.1. Filtered Back Projection [1.9]
 - 14.1.10.2. Iterative Reconstruction (e.g. MLEM, OSEM) [2.8]
 - 14.1.10.3. Sensitivity and Resolution [2.8]
 - 14.1.10.4. Matrix Size [2.8]
 - 14.1.10.5. Resolution Recovery (PSF Reconstruction) [1.6]
- 14.2. Effective Use
 - 14.2.1. Clinical Quantitative Imaging [2.4]
 - 14.2.1.1. Thyroid and Parathyroid [2.6]
 - 14.2.1.2. Renal [2.6]
 - 14.2.1.3. Cardiac (Ejection Fraction, Myocardial Perfusion) [2.6]
 - 14.2.1.4. Ventilation Perfusion (VQ) [2.6]
 - 14.2.1.5. Multi-energy Imaging [2.3]
 - 14.2.1.6. Gall Bladder (Ejection Fraction) [2.6]
 - 14.2.1.7. Gastric Emptying [2.8]
 - 14.2.2. Single Photon Emission Computed Tomography (SPECT) and SPECT/CT [3.0]
 - 14.2.2.1. Clinical Utilization [2.9]
 - 14.2.2.2. Mechanisms of Operation [2.8]
 - 14.2.2.2.1. Single- and Multi-Head Units [2.9]
 - 14.2.2.2.2. Rotational Arc [2.3]
 - 14.2.2.2.2.1. Continuous Motion [1.5]
 - 14.2.2.2.2.2. Step-and-Shoot [2.0]
 - 14.2.2.2.2.3. Noncircular Orbits [2.3]
 - 14.2.2.2.2.4. Number of Steps (Views and Frames) [2.8]
 - 14.2.3. Positron Emission Tomography (PET) and PET/CT [2.9]
 - 14.2.3.1. Clinical Utilization [2.6]
 - 14.2.3.1.1. Oncology (e.g. FDG) [2.8]

- 14.2.3.1.2. Neurology (e.g. Florbetapir) [2.8]
 - 14.2.3.1.3. Cardiac (e.g. Rb) [2.5]
 - 14.2.3.2. Attenuation Correction [2.9]
 - 14.2.3.3. Standardized Uptake Value (SUV) and Contributing Factors [2.9]
- 14.3. Image Characteristics and Artifacts
 - 14.3.1. Spatial Resolution [2.9]
 - 14.3.2. Sensitivity [2.9]
 - 14.3.3. Noise [2.9]
 - 14.3.4. Count Rate and Administered Activity Considerations [2.9]
 - 14.3.5. Artifacts [2.9]
 - 14.3.5.1. NM Instrumentation Sources (e.g., Non-uniformity, Collimator, Improper Energy Peaking, etc.) [2.8]
 - 14.3.5.2. NM Patient Sources (e.g., Attenuation Correction, Motion, Foreign Object, etc.) [2.8]
 - 14.3.5.3. PET Instrument Sources (e.g., Block Loss, Misregistration, etc.) [2.9]
 - 14.3.5.4. PET Patient Sources (e.g., High Serum Glucose, Motion, Attenuation Correction, etc.) [2.8]
- 14.4. Safety, Quality Management and Regulatory Issues
 - 14.4.1. Radiation Protection [3.0]
 - 14.4.1.1. Facility Design [1.6]
 - 14.4.1.1.1. Transport and Receiving of Radioactive Sources [2.5]
 - 14.4.1.1.1.1. Transportation Index [2.5]
 - 14.4.1.1.1.2. Storage [2.5]
 - 14.4.1.1.1.3. Labeling and Logs [2.4]
 - 14.4.1.1.2. Structural Shielding (No Calculations) [1.5]
 - 14.4.1.2. Occupational Exposure [2.8]
 - 14.4.1.2.1. Protective Measures [2.8]
 - 14.4.1.2.2. Personal Monitoring [2.8]
 - 14.4.1.2.3. Shielding of Radionuclides (Gamma, Betas) [2.9]
 - 14.4.1.3. Exposure from Patients [2.9]
 - 14.4.1.3.1. Release criteria [3.0]
 - 14.4.1.4. Radioactive Material Spills [2.9]
 - 14.4.1.5. Radiopharmacy [2.4]
 - 14.4.1.5.1. Wipe Tests and Daily Surveys [2.3]
 - 14.4.1.5.2. Surface Contamination Doses [2.3]
 - 14.4.1.5.3. Radioactive Waste Records [2.3]
 - 14.4.1.6. Internal Dose Assessment [2.6]
 - 14.4.1.6.1. Effective Half-Life [2.9]
 - 14.4.1.6.2. Medical Internal Radiation Dose (MIRD) Formalism [2.8]
 - 14.4.1.7. Regulatory and Accreditation Requirements [2.6]
 - 14.4.1.7.1. Nuclear Regulatory Commission (NRC) [2.6]
 - 14.4.1.7.2. Agreement States [2.6]
 - 14.4.1.7.3. Other Agencies (EPA, FDA, DOT, etc.) [2.3]
 - 14.4.1.8. Radiation Emergencies and Disaster Plans [1.8]
 - 14.4.2. Radiation Detection Instrumentation [2.9]
 - 14.4.2.1. Gas-Filled Detectors [2.8]
 - 14.4.2.1.1. Mechanisms of Operation [2.8]
 - 14.4.2.1.2. Applications and Limitations [2.8]

- 14.4.2.1.3. Survey Meters (e.g., GM Counter, Ionization Chamber) [2.8]
- 14.4.2.1.4. Dose Calibrator [2.9]
- 14.4.2.1.5. Quality Control [2.8]
- 14.4.2.2. Scintillation Detectors [2.9]
 - 14.4.2.2.1. Mechanisms of Operation [2.8]
 - 14.4.2.2.2. Applications and Limitations [2.6]
 - 14.4.2.2.3. Pulse-Height Spectroscopy [2.8]
 - 14.4.2.2.4. Thyroid Probe [1.9]
- 14.4.2.3. Photomultiplier Tube (PMT) [2.5]
- 14.4.2.4. New Technological Innovations (e.g., Solid State Cameras, Cardiac Gamma Cameras, etc.) [2.4]
- 14.4.3. Well Counter Quality Control [2.4]
- 14.4.4. Solid State Detectors [2.0]
- 14.4.5. Nuclear Medicine Therapy [2.6]
 - 14.4.5.1. Radiopharmaceuticals [2.6]
 - 14.4.5.1.1. I-131 Sodium Iodide [3.0]
 - 14.4.5.1.2. Y-90 Microspheres [3.0]
 - 14.4.5.1.3. Ra-223 Dichloride [2.4]
 - 14.4.5.1.4. Sm-153 EDTMP [1.4]
 - 14.4.5.2. Regulatory Considerations [2.4]
 - 14.4.5.3. Clinical Utilization [2.5]
 - 14.4.5.4. Written Directive [3.0]
 - 14.4.5.5. Patient Safety and Release Considerations (See also Module 7) [2.8]
- 14.4.6. Factors Affecting Public, Staff, and Unintended Patient Dose (See also Module 7) [2.6]
- 14.4.7. Counting Statistics
 - 14.4.7.1. Poisson Distribution [1.5]
 - 14.4.7.2. Propagation of Error (Gross, Net, and Background Counts) [1.1]
 - 14.4.7.3. Uncertainty, Standard deviation and Coefficient of Variation [1.1]
- 14.4.8. Quality Assurance and Quality Control [2.8]
 - 14.4.8.1. QC Phantoms [2.1]
 - 14.4.8.2. NM Testing (e.g., Center of Rotation, Uniformity, etc.) [2.8]
 - 14.4.8.3. PET Testing (e.g., SUV, Uniformity, etc.) [2.8]
 - 14.4.8.4. CT Registration [2.5]
- 14.5. Modality-Specific References:
 1. Mettler, F.A., Guiberteau, M.J. *Essentials of Nuclear Medicine Imaging*, 6th ed. Elsevier, 2012.
 2. Cherry, S.A., Sorenson, J.A.. *Physics in Nuclear Medicine*. Elsevier, 2012.

Example Q&A:

Q1. (Safety, Quality Management, Regulations) A licensee may release any individual who has been administered radioactive material if the total effective dose equivalent to any other individual from exposure to the released individual is not likely to exceed what value?

- A. 1 mSv
- B. 5 mSv
- C. 15 mSv
- D. 50 mSv

Answer: B – 5 mSv

Explanation: 10 CFR 35.75 (a) states: “A licensee may authorize the release from its control of any individual who has been administered unsealed byproduct material or implants containing byproduct material if the total effective dose equivalent to any other individual from exposure to the released individual is not likely to exceed 5 mSv (0.5 rem).”

Reference:

Code of Federal Regulation Title 10 Part 35.75

Q2. (Effective Use) An incorrect patient weight is entered into a PET scanner. The incorrect patient weight is 100 kg greater than the actual weight of the patient. What effect will the incorrect patient weight have on the Standard Uptake Value (SUV) reported by the scanner?

- A. Reported SUV value is correct
- B. Reported SUV value greater than the correct SUV value
- C. Reported SUV value less than the correct SUV value

Answer: B – Reported SUV value greater than the correct SUV value

Explanation: $SUV = \text{mean ROI activity (mCi/mL)} / \text{administered activity (mCi/g)}$. Inadvertently adding 100 kg to the patient weight reduces the administered activity concentration. The administered activity is in the denominator of the SUV equation. A reduction in the value of the administered activity results in an increase in the value of the SUV.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Mettler, F.A. and Guiberteau M.J. *Essentials of Nuclear Medicine Imaging* 6th ed. Philadelphia: Saunders Elsevier, 2012

Q3. (Underlying Technology and Physical Principles) Why does I-131 deliver 100 times more dose to the thyroid per mCi than I-123?

- A. Higher energy Gamma Radiation
- B. Abundance of Beta Radiation
- C. Longer Half Life
- D. Greater Specific Activity

Answer: B – Abundance of Beta Radiation

Explanation: Beta particles emitted from I131 only. These are highly energetic and deposit their dose less than a centimeter from the source.

References:

1. "MIRD Dose Estimate Report No. 5." *J. Nucl. Med.* 16(9), 1975.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q4. (Safety, Quality Management, and Regulatory) According to NRC regulations, the administered activity must be within what percentage of the prescribed activity?

- A. 5%
- B. 10%
- C. 15%
- D. 20%

Answer: D – 20%

Explanation: 10 CFR Part 35.63(d) states, "Unless otherwise directed by the authorized user, a licensee may not use a dosage if the dosage does not fall within the prescribed dosage range or if the dosage differs from the prescribed dosage by more than 20 percent."

Reference: Code of Federal Regulations, Title 10, Part 35.63(d)

Q5. (Underlying technology and Physical Principles) What is the effective half-life of Tc-99m in an organ if its biological half-life is 3 hours?

- A. 2 hours
- B. 3 hours
- C. 6 hours
- D. 9 hours

Answer: A – 2 hours

Explanation: The effective half-life is used in the MIRD schema to take into account biological elimination from the body and physical decay of the radionuclide. The effective half-life can be calculated using the formula: $1/T_{\text{eff}} = (1/T_b) + (1/T_p)$. T_{eff} is the effective half-life, T_b is the biological half-life, and T_p is the physical half-life. The physical half-life of Tc-99m is 6 hours. In this case: $1/T_{\text{eff}} = (1/3 \text{ hours}) + (1/6 \text{ hours}) = 3/6 \text{ hours}$. $T_{\text{eff}} = 2 \text{ hours}$.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Huda, W. *Review of Radiologic Physics*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2016.

Q6. (Effective Use) What collimator should be used when imaging Indium-111?

- A. Low energy
- B. Medium energy
- C. High energy

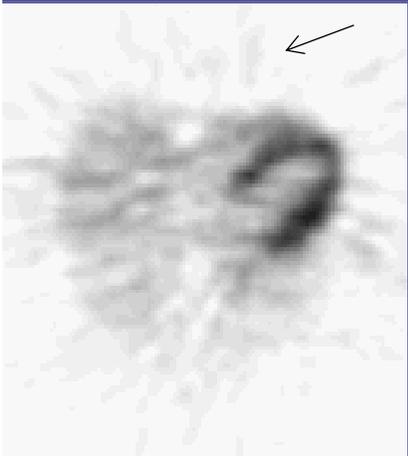
Answer: B – Medium energy

Explanation: In-111 emits gamma rays at 171 keV and 245 keV. Lead septae in low-energy collimators are too thin to effectively block these photons, so a medium-energy collimator is used. A high-energy collimator would block the photons and provide good localization, but it also blocks more of the desired photons and thus is less efficient than the medium-energy collimator.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Mettler, F.A. and Guiberteau M.J. *Essentials of Nuclear Medicine Imaging* 6th ed. Philadelphia: Saunders Elsevier, 2012

Q7. (Image Characteristics and Artifacts) What reconstruction algorithm causes the streaking artifact outside the body as indicated by the arrow in the cardiac perfusion image?



(Image credit: Jonathon A. Nye, PhD, Emory University)

- A. Filtered backprojection
- B. Conjugate gradient
- C. Ordered-subset expectation maximization
- D. Bayesian penalization

Answer: A – Filtered backprojection

Explanation: The application of filtered back projection assumes that the data collected are perfectly sampled in the radial direction (e.g., no gaps), noise free, and equivalent no matter where the activity is in the FOV (e.g., depth of interaction problem in PET). The breakdown of these assumptions results in streaks in the image, most evident by interleaving positive and negative lines radiating from the image. These streaks are particularly evident outside the image and near hot structures.

Reference:

1. Cherry, Sorenson, and Phelps. *Nuclear Medicine Physics*, 3rd ed. Elsevier.

Q8. (Effective Use) The following gamma camera bone image was collected with the camera head placed 30 cm from the body. If the patient were to be rescanned, what can be done to improve the spatial resolution of the image?



(Image credit: Naddaf, et al. “Technical Errors in Planar Bone Scanning.” *JNM* 32:148, 2004.)

- A. Increase the total number of counts
- B. Use a larger pixel matrix
- C. Move the camera closer to the patient
- D. Applied a post-image smoothing filter

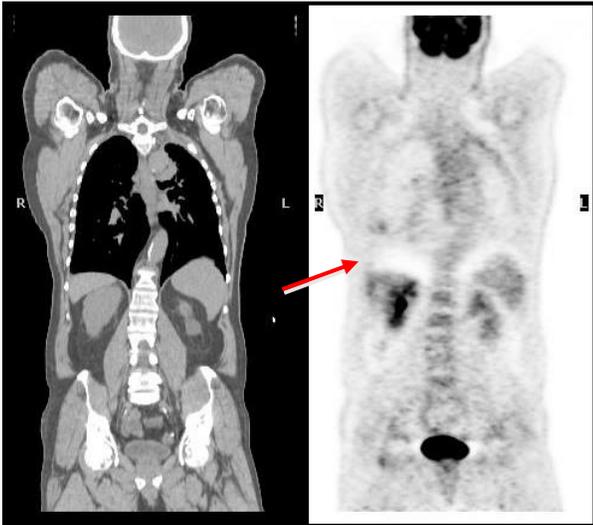
Answer: C – Move the camera closer to the patient

Explanation: The spatial resolution of planar gamma camera images is dependent on the distance from the source (e.g., depth dependence).

Reference:

1. Naddaf, et al. “Technical Errors in Planar Bone Scanning.” *JNM* 32:148, 2004.)

Q9. (Image Characteristics and Artifacts) What is the cause of the photopenic area at the diaphragm–lung interface of the right image compared to the left FDG PET/CT coronal image?



(Image credit. Tinsu Pan, PhD, MD Anderson Cancer Center)

- A. Scatter correction error
- B. Respiratory motion misregistration
- C. Non-attenuation corrected reconstruction
- D. Non-metabolic mass

Answer: B – Respiratory motion misregistration

Explanation: The temporal resolution between the CT and PET are not matched at the interface between the liver and diaphragm. This has caused a situation where liver present in the PET, is not accurately represented in the CT, therefore the attenuation correction leads to an under correction at this boundary.

References:

1. Pan, et al. “Attenuation correction of PET images with respiratory-averaged CT images in PET/CT.” *JNM* 46:1481, 2005.
2. Truong, et al. “Pitfalls in integrated CT-PET of the thorax: implications in oncologic imaging.” *J. Thoracic Imaging* 21:111–22, 2006.

Q10. (Image Characteristics and Artifacts) What can be determined from the image quality of the dynamic planar Tc-99m DTPA study of the kidneys?



(Image reference: *IAEA Quality Control Atlas for Scintillation Camera Systems*. Vienna: IAEA, 2003.)

- A. The collimator is damaged
- B. Improperly tuned photomultiplier tubes
- C. Injection site extravasation
- D. Damaged patient table

Answer: B – Improperly tuned photomultiplier tubes

Explanation: The acquisition protocol that resulted in the artifact on the left side of the patient started with a static acquisition and transitioned to a continuous bed acquisition. An improperly tuned or damaged PMT is evident by the focal spot of concentrated counts. As the continuous bed motion starts, the improperly responding PMT creates a linear streak down the length of the image.

Reference:

1. *IAEA Quality Control Atlas for Scintillation Camera Systems*. Vienna: IAEA, 2003.

Q11. (Effective Use) What is the primary reason that 180° RAO-LPO instead of 360° acquisition orbits are used for cardiac SPECT?

- A. Speed up data collection
- B. Reduce attenuation
- C. Improve patient comfort
- D. Permit use of MLEM reconstruction

Answer: B – Reduce attenuation

Explanation: The RAO-LPO orbit keeps the camera closest to the heart along the chest wall, where attenuation and distance to the heart is minimized. These actions improve contrast and resolution in the reconstructed images. An 180° orbit along the back of the body or a full 360° orbit results in several projects receiving low counts, higher amount of scatter signal, and reduced resolution due to the larger distance between the heart and camera head. High noise projections dominate the noise in the reconstructed SPECT slices.

Reference:

1. Iskandrian, A. and E. Garcia. *Nuclear Cardiac Imaging: Principles and Applications*, 5th ed. Oxford University Press, 2008.

Q12. (Underlying Technology and Physical Principles) What is the purpose of photomultiplier tubes in nuclear medicine instrumentation?

- A. Detect electron-ion pairs and convert them to current
- B. Convert visible light into electrical signal
- C. Integrate charge to be read out at a later time
- D. Focus gamma rays onto the crystal

Answer: B – Convert visible light into electrical signal

Explanation: PMT are constructed with a photocathode followed by a series of dynodes. The role of the photocathode is to convert light from crystal excitation to a proportionate number of electrons. Then the dynodes amplify the signal by a factor of approximately 10^6 .

Reference:

1. Cherry, Sorenson, Phelps. *Physics in Nuclear Medicine*, 3rd ed. Elsevier, 2003.