Diagnostic Radiology Residents Physics Curriculum

AAPM Subcommittee of the Medical Physics Education of Physicians Committee

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Authors: See complete list in Appendix A

History and comments: See complete details in Appendix B

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. The subject material described in this curriculum should be taught in a clinically relevant manner; the depth and order of presentation is left to the institution.

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. The ABR Exam of the Future (EOF) will affect radiology residents who enter residency programs in 2010 or later, with the first core exam to be given in 2013. The ABR certification in diagnostic radiology is to be divided into two examinations, the first covering basic/intermediate knowledge of all diagnostic radiology and a second certifying exam covering the practice of diagnostic radiology. The first exam will be broken into three primary categories: 1) fundamental radiologic concepts, 2) imaging methods, and 3) organ systems. This curriculum is designed to address the fundamental radiologic concepts and imaging methods categories directly. The last category on organ systems is not addressed directly within the curriculum; however, the educator needs to continuously associate the concepts within the modules to different organ systems to assure that the clinical applications are evident.

The question sets contained in this curriculum were created to provide additional educational materials for teaching residents as well as for resident self-education. 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. It is likely that some of the information contained in these question sets will appear in some form on the ABR examination due to the importance of these concepts. Committee members who are item writers for the current ABR examinations abstained from contributing content for these question sets.

This curriculum contains 17 modules covering imaging physics. The first nine modules cover basic radiation physics and biology, and the remaining modules utilize this base information to examine

clinical applications of physics to each modality. Each module presents its content in three sections: (1) learning objectives, (2) concise syllabus, and (3) detailed syllabus.

The first section of each module presents the learning objectives for the module. These learning objectives are organized into three subsections: (1) fundamental knowledge relating to module concepts, (2) specific clinical applications of this knowledge, and (3) topics to permit demonstration of problem-solving based on the previous sections. The clinical applications and problem-solving subsections contain concepts that a resident should be able to understand and answer following completion of each module.

The second area within each module presents concise syllabi that delineate the concepts the module is addressing. These concise syllabi may be used as an outline for a course in imaging physics. Not all areas of each concise syllabus module need be taught with the same emphasis or weight, so long as the student can demonstrate an understanding of the educational objectives and solve clinically relevant problems. The concise syllabus should be considered a base or minimal curriculum to present the educational objectives.

The last area within each module is a detailed syllabus that expands upon the concise syllabus and provides a more thorough coverage of each subject. The detailed syllabus is presented as a guide to the instructor providing specific topic details that may be needed to cover a subject more thoroughly.

Module 1: Structure of the Atom

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

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 structure and associated energy levels define its chemical and 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.

Clinical Application:

None

Clinical Problem-solving:

None

Concise Syllabus:

Same as detailed curriculum

Detailed Curriculum:

1. Structure of the Atom
    - 1.1. Composition
        - 1.1.1. Electrons
        - 1.1.2. Nucleus
    - 1.2. Electronic Structure
        - 1.2.1. Electron Orbits
        - 1.2.2. Orbital Nomenclature
        - 1.2.3. Binding Energy
        - 1.2.4. Electron Transitions
        - 1.2.5. Characteristic Radiation
        - 1.2.6. Auger Electrons
    - 1.3. Nuclear Structure
        - 1.3.1. Composition
        - 1.3.2. Nuclear Force
        - 1.3.3. Mass Defect
        - 1.3.4. Binding Energy
        - 1.3.5. Nuclear Instability–Overview

Example Q&A:

Q1. The maximum number of electrons in the outer shell of an atom is:

A. $2n^2$
B. 8
C. 16
D. 32
E. 2

Answer: A – $2n^2$

Explanation: The arrangement of electrons outside the nucleus is governed by the rules of quantum mechanics and the Pauli exclusion principle. Accordingly, the maximum number of electrons in an orbit is given by $2n^2$, where n is the orbit number. The innermost orbit or shell is called the K-shell, followed by L-, M-, N-, and O-shells. Hence, a maximum of 2 electrons can exist in the K-shell, 8 in the L-shell, and 18 in the M-shell.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002.

Q2. 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 different numbers 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.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002.

Q3. The mass number (A) of an atom is equal to the sum of the:

A. neutrons
B. protons
C. neutrons and protons
D. protons and electrons

E. atomic masses plus the total binding energy

Answer: C – neutrons and protons

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

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002.

Q4. 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 to the L-shell from the K-shell
C. the energy needed for an electron to jump from the L-shell to K-shell
D. the energy needed to remove an electron from the K-shell
E. none of the above

Answer: D – the energy needed to remove an electron from the K-shell

Explanation: The binding energy of an electron at a certain shell is defined as the energy needed to remove that electron from the specific shell.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002.

Q5. A proton is electrostatically repelled by:

A. electrons
B. neutrons
C. positrons and neutrons
D. alpha particles and electrons
E. positrons and alpha particles

Answer: E – positrons and alpha particles

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.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002.

Module 2: Electromagnetic (EM) Radiation

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Describe the wave and particle characteristics of electromagnetic (EM) radiation.
2. Within the EM radiation spectrum, identify the properties associated with energy and the ability to cause ionization.

Clinical Application:

1. Explain how the relative absorption of electromagnetic radiation in the body varies across the electromagnetic energy spectrum.

Clinical Problem-solving:

None

Concise Syllabus:

Same as detailed curriculum

Detailed Curriculum:

2. Electromagnetic (EM) Radiation
   - 2.1. Wave–Particle Duality
     - 2.1.1. Wave Characteristics
     - 2.1.2. Particle Characteristics
   - 2.2. Electromagnetic Spectrum
     - 2.2.1. Ionizing
     - 2.2.2. Non-ionizing

Example Q&A:

Q1. All but which of the following modalities uses electromagnetic radiation during diagnostic imaging procedures?

A. fluoroscopy
B. mammography
C. MRI
D. ultrasound
E. CT

Answer: D – ultrasound

Explanation: Ultrasound is produced when electrical energy is converted into mechanical energy. This mechanical energy causes molecules in a compressible medium to move, which generates ultrasound energy. Unlike electromagnetic radiation, ultrasound propagation requires transmission though a medium, and its interactions are determined by the acoustic properties of the medium. Its wavelength is dependent on the medium.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*. Philadelphia: Lippincott Williams & Wilkins, 1994, p. 372.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 469–477.

Q2. Electromagnetic radiation can be categorized as either ionizing or non-ionizing radiation. The principle characteristic that determines this function is:

A. wavelength
B. frequency
C. energy
D. speed
E. transmission media

Answer: C – energy

Explanation:
Frequency and energy are directly related, but ionization depends on the photon having enough energy to transfer to the bound electrons to enable their release. The minimum energy needed to remove an electron from water is 12.6 eV. Energy is also a primary factor when atoms gain electrons. Energy absorbed that is not sufficient to produce ionization may cause excitation. This occurs with non-ionizing EM radiation.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*. Philadelphia: Lippincott Williams & Wilkins, 1994, p. 5.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 19.

Q3. The electromagnetic spectrum is a continuum of electric and magnetic energies that vary in wavelength and frequencies. Identify which of the following are utilized in diagnostic imaging:

A. radiofrequency, infrared, visible light
B. infrared, visible light, UV
C. radiofrequency, visible light, x-ray
D. ultraviolet, x-ray, gamma rays
E. x-rays, gamma rays

Answer: C – radiofrequency, visible light, x-ray

Explanation: RF is the transmission and reception signal for MRI imaging. Visible light is produced in detecting x- and gamma radiation and is used to observe and interpret images (film). X-rays are the primary form used to produce images.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*. Philadelphia: Lippincott Williams & Wilkins, 1994, p. 3.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 17.

Q4. Historically, different forms of electromagnetic radiation have been used in medical imaging to identify abnormalities. Except for one category, all of the following have been used for breast imaging. Identify that category.

A. radiofrequency
B. infrared
C. visible light
D. ultraviolet
E. gamma rays

Answer: D – ultraviolet

Explanation: RF is used in MRI imaging of the breast. Infrared is used in thermography. Visible light is used for in diaphanography where a breast is illuminated by a low-intensity light, and the transmission pattern of red and near-infrared radiation is detected either digitally or photographed on infrared-sensitive film. Nuclear medicine imaging utilizes gamma radiation and is sometimes used to augment x-ray mammography in addition to MRI and ultrasound.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 192–3.
2. Webb, S., ed. *The Physics of Medical Imaging*. London: Institute of Physics, 1988, p. 578.

Q5. The electromagnetic spectrum is a continuum of electric and magnetic energies that vary in wavelength and frequencies. Identify which of the following are classified as ionizing radiation.

A. radiofrequency, infrared, visible light
B. infrared, visible light, UV
C. radiofrequency, visible light, x-ray
D. ultraviolet, x-ray, gamma rays
E. x-rays, gamma rays

Answer: D – ultraviolet, x-ray, gamma rays

Explanation:
Higher-energy UV can cause ionization as well as x-ray and gamma rays, which are at the higher frequency and energy range of the EM spectrum. As such, there is enough energy per UV, x-ray, and gamma photons to enable the release of bound electrons. The general threshold energy for ionization is approximately 10 eV. To ionize water, the minimum energy to remove an electron is 12.6 eV.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*. Philadelphia: Lippincott Williams & Wilkins, 1994, p. 5–6.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 17–19.

Module 3: Particulate Radiation

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Identify the different categories and properties of particulate radiation.

Clinical Application:

None

Clinical Problem-solving:

None

Concise Syllabus:

Same as detailed curriculum

Detailed Curriculum:

3. Particulate Radiation
   - 3.1. Light Particles
   - 3.2. Heavy Charged Particles
   - 3.3. Uncharged Particles
     - 3.3.1. Neutrons
     - 3.3.2. Neutrinos

Example Q&A:

Q1. Which of the following is an example of high linear energy transfer (LET) particulate radiation? NOTE: Assume all energies are in the diagnostic range (roughly, 0–0.5 MeV).

A. microwaves
B. electron beam
C. proton beam
D. gamma Rays

Answer: C – proton beam

Explanation: Only electron and proton beams are particulate. Electrons are low LET radiation and protons are high LET 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*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2010.

Q2. The energy of each photon created when a positron almost at rest interacts with an electron in an annihilation reaction is:

A. 5 eV
B. 144 keV
C. 511 keV
D. 1 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, each photon gets ½ the total energy, or 511 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*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2010.

Q3. The Bragg peak is associated with:

A. electrons
B. x-rays
C. microwaves
D. protons

Answer: D – protons

Explanation: X-rays and microwaves undergo exponential attenuation as they traverse a material. Electrons do not exhibit a Bragg peak because they undergo multiple scattering interactions and radiative losses. Protons, which are 2000 times more massive than electrons, travel in essentially straight lines with little or no radiative losses. At the end of their range, the dose per unit length rises rapidly, creating the "Bragg peak."

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Hendee, W.R. and E.R. Ritenour. *Medical Imaging Physics*, 4th ed. New York: Wiley–Liss, 2002.

Q4. In the event of an I-131 spill (non-liquid), which of the organs below is at greatest risk of deterministic damage?

A. skin
B. brain

C. liver
D. heart

Answer: A – skin

Explanation: The majority of dose is radiated as beta particles, which have a short finite range and are unlikely to penetrate to deep organs of the body. I-131 also emits high-energy photons, however these are not an immediate concern for deterministic damage.

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.

Q5. Place the following in increasing order of damage to tissue.

A. electron, neutrino, proton (100 keV), photon (diagnostic energy)
B. photon (diagnostic energy), electron, proton (100 keV), neutrino
C. neutrino, photon (diagnostic energy), electron, proton (100 keV)
D. proton (100 keV), neutrino, photon (diagnostic energy), electron

Answer: C – neutrino, photon (diagnostic energy), electron, proton (100 keV)

Explanation: Neutrinos are near massless particles that undergo almost no interactions with any matter (many penetrate Earth without interacting). Low-energy 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 due to the presence of a Bragg peak.

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.

Q6. A pancake meter records dose when an unshielded detector is swept over a spill, but no dose 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.

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.

Q7. A person accidentally imbibes an unknown radioactive substance and lives in close proximity with his or her family for several hours before realizing the mistake and going to the hospital. Which of the following types of radiation is the greatest safety concern for the family?

A. photons (300 keV)
B. protons
C. electrons (30 keV)
D. alpha particles

Answer: A – photons (300 keV)

Explanation: Protons, 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.

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 4: Interactions of Ionizing Radiation with Matter

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

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 are attenuated (i.e., absorbed and scattered) within a material and the terms used to characterize the attenuation.

Clinical Application:

1. Identify which photon interactions are dominant for each of the following imaging modalities: mammography, projection radiography, fluoroscopy, CT, and nuclear medicine imaging procedures.
2. Understand how image quality and patient dose are affected by these interactions.
3. What are the appropriate x-ray beam energies to be used when iodine and barium contrast agents are used?
4. How does the type of photon interaction change with increasing energy, and what is the associated clinical significance?

Clinical Problem-solving:

1. Select an appropriate thyroid imaging agent based on its particulate emissions for pediatric imaging and for adult imaging. Would these agents use the same isotopes or different isotopes? How does dose differ between these imaging isotopes?
2. What is the purpose of adding Cu filters in vascular imaging?
3. What makes a contrast agent radiolucent instead of radio-opaque?

Concise Syllabus:

Same as detailed curriculum

Detailed Curriculum:

4. Interactions of Ionizing Radiation with Matter
    - 4.1. Charged-particle Interactions
        - 4.1.1. Ionization and Excitation
        - 4.1.2. Bremsstrahlung
        - 4.1.3. Secondary Ionization
            - 4.1.3.1. Specific Ionization
            - 4.1.3.2. Linear Energy Transfer (LET)
        - 4.1.4. Positron Annihilation
    - 4.2. Photon Interactions
        - 4.2.1. Coherent Scattering
        - 4.2.2. Compton Scattering
        - 4.2.3. Photoelectric Effect
        - 4.2.4. Interactions in Tissues
        - 4.2.5. Contrast Media

4.3. Photon Attenuation
  4.3.1. Linear Attenuation Coefficient
  4.3.2. Attenuation Equation
  4.3.3. Mono-Energetic and Poly-Energetic X-ray Beams
  4.3.4. Half-Value Layer (HVL)
    4.3.4.1. Effective Energy
    4.3.4.2. Beam Hardening

Example Q&A:

Q1. The predominant interaction of 120 kVp x-rays from a computed tomography scanner with soft tissue is:

A. coherent scattering
B. Compton scattering
C. photoelectric effect
D. pair production

Answer: B – Compton scattering

Explanation: Above 25–30 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 kVp (70 keV).

References:

1. RSNA/AAPM. Online Physics Module – "Interactions of Radiations and Tissue."
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q2. If a radiologic technologist increases the kVp from 70 to 90 during an AP projection of the lumbar spine, which of the following interactions will be the predominant interaction with bone during imaging with 90 kVp x rays?

A. coherent scattering
B. Compton scattering
C. photoelectric effect
D. pair production

Answer: C – photoelectric effect

Explanation: The average energy for a 90 kVp x-ray beam is approximately 1/3 to 1/2 of the kVp. Therefore 30–45 keV x-ray photons will be primarily absorbed by bone in this energy range.

References:

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

2. RSNA/AAPM. Online Physics Module – "Interactions of Radiations and Tissue."

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

A. exposure time
B. focal spot size
C. kVp
D. source-to-image receptor distance (SID)

Answer: C – kVp

Explanation: Compton scattering increases with an increase in x-ray beam energy (kVp, filtration), thickness of the part, or an increase in x-ray field size. (Both increase the number of loosely bound electrons available for interaction).

References:
1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. RSNA/AAPM. Online Physics Module – "Interactions of Radiations and Tissue."

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

A. coherent scattering
B. Compton scattering
C. photoelectric effect
D. pair production

Answer: C – photoelectric effect

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

References:
1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. RSNA/AAPM. Online Physics Module – "Interactions of Radiations and Tissue."

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 an energy of 140 keV. At this energy more than 50% of the interactions are photoelectric. (See Figure 3–11 in the Bushberg reference below.)

Reference:

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

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. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. RSNA/AAPM. Online Physics Module – "Interactions of Radiations and Tissue"

Q7. Which of the following is primarily responsible for patient dose with Iodine-131 imaging and treatment?

A. alpha particles
B. beta particles
C. gamma rays
D. neutrons

Answer: B – beta particles

Explanation: Ninety-five percent of the absorbed dose to the thyroid is from beta particles.

References:

1. RSNA/AAPM. Online Physics Module – "Radionuclide Dosimetry and Nuclear Regulations."
2. RSNA/AAPM. Online Physics Module – "Interactions of Radiations and Tissue."

Q8. The occurrence of a sharp increase in photoelectric absorption is related to which of the following factors?

A. A sharp increase in photoelectric absorption occurs as density increases.
B. A sharp increase in photoelectric absorption occurs as density decreases.
C. A sharp increase in photoelectric absorption occurs when the photon energy is just above the atomic number of the substance.
D. A sharp increase in photoelectric absorption occurs when the photon energy is just above the electron binding energy.

Answer: D – A sharp increase in photoelectric absorption occurs just above the electron binding energy.

Explanation: Photelectric 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. RSNA/AAPM. Online Physics Module – "Interactions of Radiations and Tissue/"

Q9. A radiologic technologist uses 30 mAs and 80 kVp for an AP pelvis radiograph on a pregnant patient. What is the radiation dose to an embryo located 9 cm below the anterior surface, as expressed as a percentage of the entrance skin dose?

A. The embryo radiation dose is equal to 100% of the entrance skin dose.
B. The embryo radiation dose is equal to 50 to 75% of the entrance skin dose.
C. The embryo radiation dose is equal to 12.5 to 25% of the entrance skin dose.
D. The embryo radiation dose is equal to 1 to 3% of the entrance skin dose.

Answer: C – The fetal radiation dose would be equal to 12.5% to 25% of the entrance skin dose.

Explanation: At 80 kVp, 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.

Reference:

1. RSNA/AAPM. Online Physics Module – "Interactions of Radiations and Tissue."

Q10. Which of the following is the most penetrating of the radiations listed?

A. photons from a 140 kVp x-ray beam
B. photons from Tc-99m radioactive decay
C. beta particles from F-18 radioactive decay
D. photons from F-18 radioactive decay

Answer: D – photons from F-18 radioactive decay

Explanation: For x-ray beams, the kVp and HVL define the effective energy, but in these choices the annihilation radiation (511 keV photons) is the most penetrating.

Reference:

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

Module 5: Radiation Units

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Recognize that there are two different systems for units of measurement (i.e., SI and classical) used to describe physical quantities.
2. Describe the SI and classical 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 classical units.

Clinical Application:

1. Discuss the appropriate use or applicability of radiation quantities in the health care applications of imaging, therapy, and safety.

Clinical Problem-solving:

1. Explain radiation exposure and dose quantities in lay language to a patient.

Concise Syllabus:

Same as detailed curriculum

Detailed Curriculum:

5. Radiation Units
    - 5.1. System of Units
        - 5.1.1. SI
        - 5.1.2. Classical
    - 5.2. Exposure
        - 5.2.1. Coulomb/kilogram
        - 5.2.2. roentgen (R)
    - 5.3. KERMA
        - 5.3.1. gray (Gy)
        - 5.3.2. rad
    - 5.4. Absorbed Dose
        - 5.4.1. gray (Gy)
        - 5.4.2. rad
    - 5.5. Equivalent Dose
        - 5.5.1. Radiation Weighting Factors
        - 5.5.2. sievert (Sv)
        - 5.5.3. rem
    - 5.6. Effective Dose
        - 5.6.1. Tissue Weighting Factors
        - 5.6.2. sievert (Sv)
        - 5.6.3. rem
        - 5.6.4. Reference Levels
        - 5.6.5. Importance in Radiation Protection
    - 5.7. Peak Skin Dose

Example Q&A:

Q1. The Joint Commission sentinel event criteria require estimation of:

A. effective dose
B. equivalent dose
C. average dose
D. peak skin dose
E. integral dose

Answer: D – peak skin dose

Explanation: The Joint Commission added a reporting requirement for skin doses from fluoroscopic procedures. To quote from a Joint Commission publication on interpretation of the requirement:
"As it relates to fluoroscopy, the specification of '1500 rads to a single field' refers to a location on the skin through which the fluoroscopic beam is directed. The issue here is the magnitude of the dose to that portion of the skin that receives the maximum or peak skin dose." The Joint Commission publication further states that the accumulated peak skin dose over one year should be considered in evaluating whether a sentinel event has occurred.

References:

1. Joint Commission. "Radiation Overdose as a Reviewable Sentinel Event." March 7, 2006.
2. Miller, D.L., et al. "Clinical radiation management for fluoroscopically guided interventional procedures." *Radiology* 257:321–32, 2010.

Q2. The ACR Appropriateness Criteria Relative Radiation Level Scale is given in units of:

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

Answer: D – mSv

Explanation: The Relative Radiation Level Scale, as given in Radiation Dose Assessment Introduction, is in Effective Dose (mSv). In contrast, diagnostic exam reference levels are given in a measured quantity appropriate to the modality (e.g., mR or mGy for radiographic images, R/min for fluoro, CTDI for CT).

References:

1. American College of Radiology. "ACR Appropriateness Criteria® Radiation Dose Assessment Introduction." Original review 2007. Last Review 2012.
2. Image Wisely: "How to Understand and Communicate Radiation Risk," Donald Peck, Ph.D. and Ehsan Samei, Ph.D.. American College of Radiology. Accessed November 2010. www.imagewisely.org.

Q3. 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 a 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. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p 56.
2. Hendee, W.R. and E.R. Ritenour. *Medical Imaging Physics*, 4th ed. New York: Wiley–Liss, 2002, p. 102.

Q4. The absorbed dose to the ovaries from a limited CT exam of 8 cm length, with a 2 cm thickness contiguous acquisition with the ovaries in the beam, is 8 mGy. If the study is expanded in length to cover 16 cm instead, which of the following descriptors of dose is correct?

A. The dose to the ovaries is 16 mGy.
B. The effective dose is 8 mSv.
C. The equivalent dose is 8 mSv.
D. The imparted energy is unchanged.

Answer: C – The equivalent dose is 8 mSv.

Explanation: Equivalent dose is absorbed dose multiplied by the appropriate radiation weighting factor. The radiation weighting factor for x-rays for CT is 1.0, so 8 mGy × 1 = 8 mSv. The imparted energy increases as the mass irradiated increases. The absorbed dose does not increase. The effective dose is the absorbed dose multiplied by the appropriate tissue or organ weighting factor. For gonads, the appropriate weighting factor is 0.08, so the effective dose is 0.64 mSv. Thus the correct answer is C.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, Chapter 3.
2. Huda, W. *Review of Radiologic Physics*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2010, p. 112–113.

Module 6: X-ray Production

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

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. Describe how the controls of an x-ray system affect the technique factors used in diagnostic imaging.
4. Define the attributes of an x-ray beam, including the function of filtration, spectrum of energies produced, and beam restriction.
5. Describe the heel effect and how it can be used to improve clinical radiographs.

Clinical Application:

1. Demonstrate how the x-ray tube design, target material, beam filtration, and focal spot size are optimized for a specific imaging task (e.g., mammography, interventional imaging, or CT).

Clinical Problem-Solving:

1. Analyze how changes in the x-ray system components change the image quality and dose for different procedures.

Concise Syllabus:

6. X-ray Production
   - 6.1. Properties of the X-ray Spectrum
     - 6.1.1. Bremsstrahlung
     - 6.1.2. Characteristic Radiation
   - 6.2. X-ray Tube
     - 6.2.1. Cathode
     - 6.2.2. Anode
     - 6.2.3. Application-specific Tubes
   - 6.3. High-frequency Generators
     - 6.3.1. Technique Factors
   - 6.4. X-ray Beam Modifiers
     - 6.4.1. Beam Filtration
     - 6.4.2. Collimators

Detailed Curriculum:

6. X-ray Production
   - 6.1. Properties of X-rays
     - 6.1.1. Bremsstrahlung
       - 6.1.1.1. Importance in Imaging and Dose
       - 6.1.1.2. Influence of Electron Energy
       - 6.1.1.3. Influence of Target Material
       - 6.1.1.4. Influence of Filtration
     - 6.1.2. Characteristic Radiation

6.1.2.1. Importance in Imaging and Dose
6.1.2.2. Influence of Electron Energy
6.1.2.3. Influence of Target Material
6.1.2.4. Influence of Filtration

6.2. X-ray Tube
6.2.1. Cathode
6.2.1.1. Filament
6.2.1.2. Focusing Cup
6.2.1.3. Filament Current and Tube Current
6.2.2. Anode
6.2.2.1. Composition
6.2.2.2. Configurations (e.g., Angulation, Stationary vs. Rotating)
6.2.2.3. Line-focus Principle
6.2.2.4. Focal Spot
6.2.2.5. Heel Effect
6.2.2.6. Off-focus Radiation
6.2.2.7. Tube Heating and Cooling
6.2.3. Application-specific Tubes
6.2.3.1. Mammography
6.2.3.2. CT
6.2.3.3. Interventional
6.2.3.4. Dental

6.3. High-frequency Generators
6.3.1. Technique Factors
6.3.1.1. kVp
6.3.1.2. mA
6.3.1.3. Time
6.3.1.4. Automatic Exposure Control (AEC)
6.3.1.5. Technique Charts

6.4. X-ray Beam
6.4.1. Beam Filtration
6.4.1.1. Inherent
6.4.1.2. Added (Al, Cu, Mo, Rh, other)
6.4.1.3. Minimum HVL
6.4.1.4. Shaped Filters
6.4.2. Spectrum
6.4.3. Collimators
6.4.3.1. Field Size Limitation
6.4.3.2. Light Field and X-ray Field Alignment
6.4.3.3. Effect on Image Quality

Example Q&A:

Q1. There are various dose-saving steps a fluoroscopist can take to reduce patient dose during interventional radiology procedures. Which of the following steps will increase patient radiation dose?

A. remove grids if the patient size is small

B. select more added filtration
C. use virtual collimation to adjust collimator blades
D. select a magnified FOV
E. reduce the pulse rate in pulsed fluoroscopy

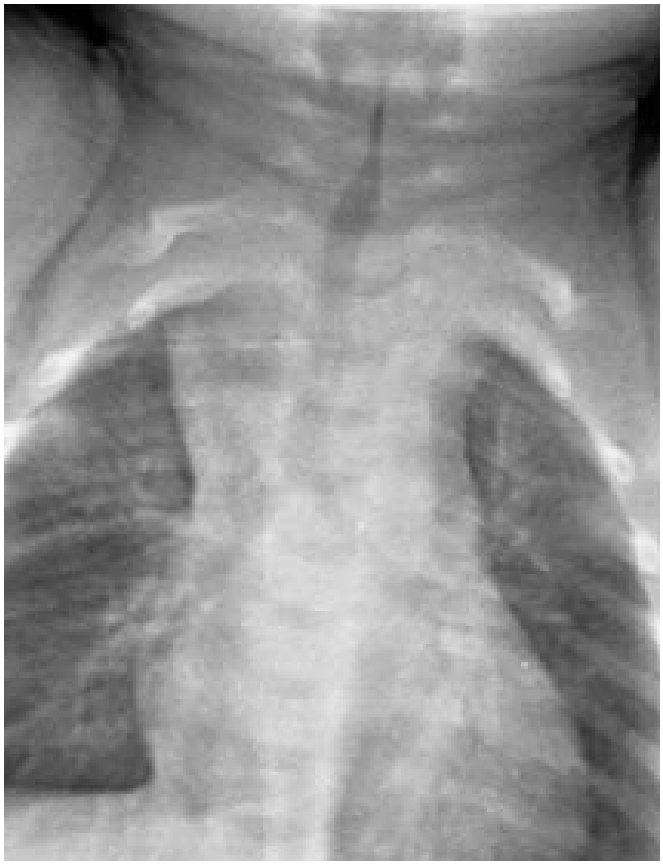
Answer: D – select a magnified FOV

Explanation: The patient dose is related to $(FOV)^{-N}$ where $2.0 < N < 3.0$. The magnified FOV means smaller FOV and thus results in more patient dose.

References:

1. Nickoloff, E.L., et al. "Influence of flat-panel fluoroscopic equipment variables on cardiac radiation doses." *Cardiovasc. Intervent. Radiol.* 30:169–176, 2007.
2. Pooley R.A., et al. "The AAPM/RSNA physics tutorial for residents: digital fluoroscopy." *Radiographics* 21:521–534.

Q2. The following pediatric airway radiograph was obtained in the 1.5X geometric magnification mode. Which of the following is the most critical factor to ensure optimal spatial resolution?



A. added filtration
B. high kVp
C. 0.3 mm focal spot size
D. large SID (source-to-image receptor distance)
E. high mAs

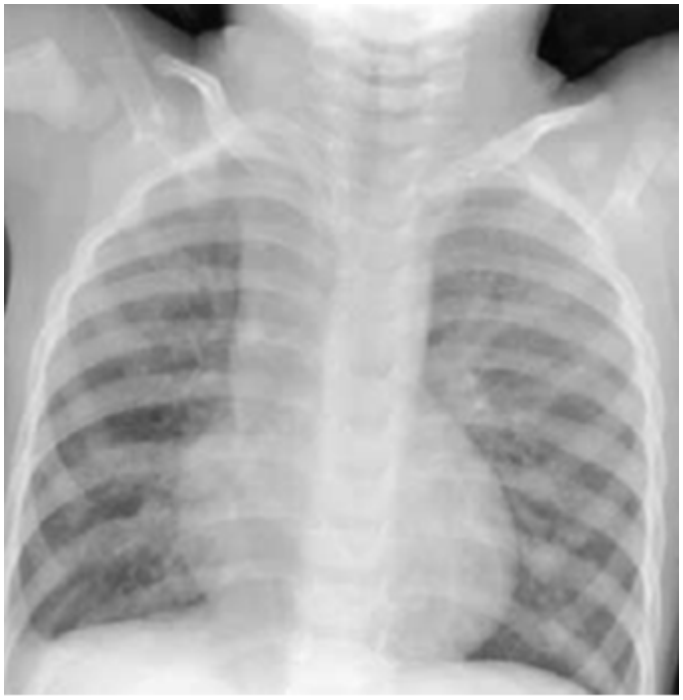
Answer: C – 0.3 mm focal spot size

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, 0.3 mm focal spot size is crucial to limit focal spot blur and, therefore, to help ensure limited geometric unsharpness and optimal spatial resolution.

References:

1. Hendee, W.R. and R. Ritenour. *Medical Imaging Physics*, 3rd ed. St. Louis: Mosby, 1992, p. 431–433.
2. Nickoloff, E.L., et al. "Pediatric high kV/filtered airway radiographs: comparison of CR and film-screen systems." *Pediatr. Radiol.* 32:476–484, 2002.

Q3. For a dedicated chest radiographic 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.

Reference:

1. Hendee, W.R. and R. Ritenour. *Medical Imaging Physics*, 3rd ed. St. Louis: Mosby, 1992, p. 129–130.

Q4. A direct result from adding additional filters to a diagnostic x-ray beam is that:

A. the characteristic radiation is removed
B. the image contrast is improved
C. the maximum photon energy is increased
D. the x-ray tube heat loading is reduced
E. the patient dose is reduced

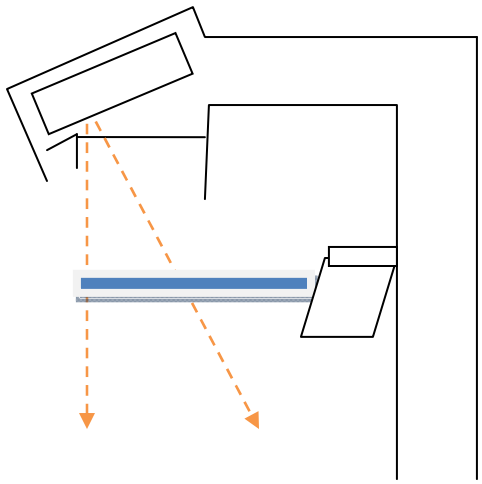
Answer: E – the patient dose is reduced.

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

References:

1. Hendee, W.R. and R. Ritenour. *Medical Imaging Physics*, 3rd ed. St. Louis: Mosby, 1992, p. 118–119.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 114.

Q5. The design of a dedicated mammography unit includes tilting the x-ray tube in a special way in order to have the central axis beam positioned at the chest wall. What is the main advantage for such a unique design?



A. to reduce heel effect and improve x-ray uniformity
B. to improve heat capacity
C. to include more breast tissues against chest wall
D. to reduce patient dose
E. to improve spatial resolution

Answer: C – to include more breast tissues against chest wall

Explanation: The central beam projects down perpendicularly. This helps include more breast tissues against the chest wall.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*. Philadelphia: Lippincott Williams & Wilkins, 1994, p. 212–214.

Q6. The appropriate focal spot size for an x-ray tube is always a trade-off between ___ and ___.

A. field of view, geometric unsharpness
B. patient dose, field of view
C. heat capacity, parallax
D. heat capacity, geometric unsharpness
E. resolution, latitude

Answer: D – heat capacity, geometric unsharpness

Explanation: The bigger the focal spot size, the greater the heat capacity. On the other hand, the bigger the focal spot size, the more the geometric unsharpness.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*. Philadelphia: Lippincott Williams & Wilkins, 1994, p. 76–78.
2. Hendee, W.R. and R. Ritenour. *Medical Imaging Physics*, 3rd ed. St. Louis: Mosby, 1992, p. 431–433.

Q7. When purchasing a new mobile radiographic system, one needs to consider the x-ray generator power rating. What would be the appropriate x-ray generator power rating for an imaging center that covers various adult clinical applications including chest, abdomen, pelvis, skull, and extremities?

A. 100 – 499 watts
B. 500 – 999 watts
C. 1,000 – 4,999 watts
D. 5,000 – 10,000 watts
E. above 10,000 watts

Answer: E – above 10,000 watts

Explanation: The power rating of a generator is the permissible load calculated in watts at 100 kVp and 0.1 sec exposure. For example, if the maximum x-ray tube current is 800 mA at 100 kVp for 0.1 sec exposure time, the power (watts) = $100 \times 10^3 \times 800 \times 10^{-3} = 80{,}000$ watts.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*. Philadelphia: Lippincott Williams & Wilkins, 1994, p. 102.

Q8. Geometric unsharpness increases with
A. moving a patient close to the image receptor
B. increased focal spot size
C. longer exposure time
D. lower kVp
E. more added filtration

Answer: B – increased focal spot size

Explanation: The geometric unsharpness is proportional to focal spot size. It is also proportional to (m – 1) where m is the magnification factor.

Reference:

1. Hendee, W.R. and R. Ritenour. *Medical Imaging Physics*, 3rd ed. St. Louis: Mosby, 1992, p. 431–433.

Q9. The patient skin dose will be reduced by using:

A. more added filtration
B. higher grid ratio
C. lower kVp
D. smaller focal spot size
E. none of the above

Answer: A – more added filtration

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

References:

1. Hendee, W.R. and R. Ritenour. *Medical Imaging Physics*, 3rd ed. St. Louis: Mosby, 1992, p. 118–119.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 114.

Q10. Heel effect is more pronounced when:

A. the image receptor is farther from the focal spot
B. using a large focal spot size
C. using a smaller image size
D. using no grid
E. using an x-ray tube with a smaller target angle

Answer: E – using an x-ray tube with a smaller target 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 target angle is small.

References:

1. Hendee, W.R. and R. Ritenour. *Medical Imaging Physics*, 3rd ed. St. Louis: Mosby, 1992, p. 129–130.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*. Philadelphia: Lippincott Williams & Wilkins, 1994, p. 78–80.

Module 7: Basic Imaging Science and Technology

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Define the methods used to describe the uncertainty in a measurement and how to use data to propagate these uncertainties through a calculation.
2. Describe the different methods for representing image data, and identify the attributes used to assess the quality of the data acquired or an imaging system.
3. Describe the different processes used to convert the acquired raw data into a final image used for interpretation.
4. Review the methods and technology used to display image data accurately and consistently.
5. Associate the characteristics of the human visual system with the task of viewing image data and the metrics used to assess an observer's response to the data.
6. Describe the purpose of IHE, DICOM, and HL7.

Clinical Application:

1. Calculate the statistical significance of a measurement or a combination of measurements.
2. Determine how changes in each image processing procedure impact the final image produced, and evaluate how these changes affect the image of different objects or body parts and their associated views.
3. Determine the important aspects of designing a new radiology reading room.
4. Illustrate how the properties of the imaging system can be used to select the best system for a specific task.
5. Give examples of what is required to optimize a display system and its associated environment in viewing images for different applications.
6. Trace the information associated with a patient exam through the HIS and RIS to the PACS.

Clinical Problem-solving:

1. Explain possible causes for a series of portable chest x-ray images show blurring in the lung parenchyma.
2. Calculate the statistical significance of a measurement or a combination of measurements to determine if the data can be used for a particular purpose, e.g., quantifying radioactivity with a dose calibration instrument.
3. Choose the appropriate image processing to be used for a specific exam.
4. Use an observer performance result to determine whether there is a difference in a procedure or study compared to the standard procedure or study.

Concise Syllabus:

7. Basic Imaging Science and Technology
   - 7.1. Basic Statistics
   - 7.2. Image Properties
   - 7.3. Image Representations
     - 7.3.1. Contrast
     - 7.3.2. Spatial Resolution
     - 7.3.3. Noise
     - 7.3.4. Temporal Resolution

7.3.5. Sampling and Quantization
7.4. Image Processing
7.4.1. Pre-processing
7.4.2. Segmentation
7.4.3. Grayscale Processing
7.4.4. Frequency Processing
7.4.5. Reconstruction
7.4.6. Three-dimensional Representations
7.4.7. Image Fusion/Registration
7.4.8. Computer-Aided Detection (CAD) and Diagnosis
7.5. Display Characteristics and Viewing Conditions
7.6. Perception
7.7. Informatics

Detailed Curriculum:

7. Basic Imaging Science and Technology
7.1. Basic Statistics
7.1.1. Systematic and Random Error
7.1.2. Precision and Accuracy
7.1.3. Statistical Distributions
7.1.4. Mean, Median, and Mode
7.1.5. Standard Deviation and Variance
7.1.6. Confidence Intervals
7.1.7. Propagation of Error
7.2. Image Properties
7.2.1. Image Representations
7.2.1.1. Spatial Domain
7.2.1.2. Frequency Domain
7.2.1.3. Temporal Domain
7.2.1.4. Fourier Transform between Domains
7.2.2. Contrast
7.2.3. Spatial Resolution
7.2.3.1. Point Spread Function (PSF)
7.2.3.2. Line Spread Function (LSF)
7.2.3.3. Full-Width-at-Half-Maximum (FWHM)
7.2.3.4. Modulation Transfer Function (MTF)
7.2.4. Noise
7.2.4.1. Quantum Mottle
7.2.4.2. Electronic
7.2.4.3. Structured
7.2.4.4. Other Sources of Noise
7.2.5. Dynamic Range
7.2.6. Contrast-to-Noise Ratio (CNR), Signal-to-Noise Ratio (SNR), Detection Efficiency (e.g., DQE)
7.2.7. Temporal Resolution
7.2.8. Sampling and Quantization
7.2.8.1. Analog-to-Digital Conversion (ADC) and Digital-to-Analog Conversion (DAC)

7.2.8.2. Aliasing
7.2.8.3. Nyquist Limit
7.2.8.4. Bit Depth

7.3. Image Processing
7.3.1. Pre-processing
7.3.1.1. Non-uniformity Correction
7.3.1.2. Defect Corrections
7.3.2. Segmentation
7.3.2.1. Region of Interest (Field of View)
7.3.2.2. Value of Interest
7.3.2.3. Anatomical
7.3.3. Grayscale Processing
7.3.3.1. Window and Level
7.3.3.2. Characteristic Curves
7.3.3.3. Look-up Table (LUT)
7.3.4. Frequency Processing
7.3.4.1. Edge Enhancement
7.3.4.2. Noise Reduction
7.3.4.3. Equalization
7.3.5. Reconstruction
7.3.5.1. Simple Back-Projection
7.3.5.2. Filtered Back-Projection
7.3.5.3. Iterative Reconstruction Methods
7.3.5.4. Sinogram
7.3.6. Three-dimensional
7.3.6.1. Multi-planar Reconstruction
7.3.6.2. Maximum-intensity Projection
7.3.6.3. Volume Rendering/Surface Shading
7.3.6.4. Quantitative Assessments
7.3.7. Image Fusion/Registration
7.3.8. Computer-aided Detection and Diagnosis

7.4. Display
7.4.1. Display Technologies
7.4.1.1. Hard-copy Printers
7.4.1.2. Film
7.4.1.3. Cathode Ray Tube (CRT)
7.4.1.4. Liquid Crystal Display (LCD)
7.4.1.5. Other Displays (e.g., Plasma, Projection)
7.4.2. Display Settings
7.4.2.1. Film Quality Control
7.4.2.2. Luminance
7.4.2.3. Matrix Size
7.4.2.4. Grayscale Display Function Calibration
7.4.2.5. Display Quality Control
7.4.3. Viewing Conditions
7.4.3.1. Viewing Distance, Image, and Pixel Size
7.4.3.2. Workstation Ergonomics
7.4.3.3. Adaptation and Masking

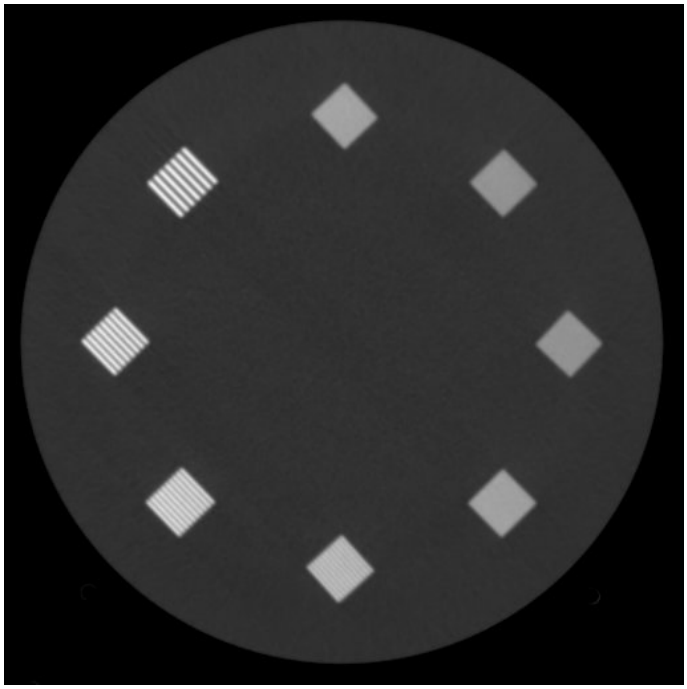
7.4.3.4. Ambient Lighting and Illuminance

7.5. Perception
- 7.5.1. Human Vision
  - 7.5.1.1. Visual Acuity
  - 7.5.1.2. Contrast Sensitivity
  - 7.5.1.3. Conspicuity
- 7.5.2. Metrics of Observer Performance
  - 7.5.2.1. Predictive Values
  - 7.5.2.2. Sensitivity, Specificity, and Accuracy
  - 7.5.2.3. Contrast-Detail
  - 7.5.2.4. Receiver Operating Characteristic (ROC) Curve
- 7.5.3. Perceptual Influence of Technology (e.g., CAD)

7.6. Informatics
- 7.6.1. Basic Computer Terminology
- 7.6.2. Integrating Healthcare Enterprise (IHE)
- 7.6.3. Picture Archiving and Communication System (PACS)
- 7.6.4. Radiology Information System (RIS), Hospital Information System (HIS)
- 7.6.5. Electronic Medical Record (EMR)
- 7.6.6. Health Level 7 (HL7)
- 7.6.7. Networks
  - 7.6.7.1. Hardware
  - 7.6.7.2. Bandwidth
  - 7.6.7.3. Communication Protocols
- 7.6.8. Film Digitizers
- 7.6.9. Storage
  - 7.6.9.1. Hardware
  - 7.6.9.2. Storage Requirements
  - 7.6.9.3. Disaster Recovery
- 7.6.10. DICOM
  - 7.6.10.1. Modality Worklist
  - 7.6.10.2. Image and Non-Image Objects
  - 7.6.10.3. Components and Terminology
  - 7.6.10.4. DICOM Conformance
- 7.6.11. Data Compression
  - 7.6.11.1. Clinical Impact
  - 7.6.11.2. Lossy
  - 7.6.11.3. Lossless
  - 7.6.11.4. Image and Video Formats
- 7.6.12. Security and Privacy
  - 7.6.12.1. Encryption
  - 7.6.12.2. Firewalls

Example Q&A:

Q1. The image of the CT phantom (displayed below) is used to measure which image property?



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. The limiting resolution is to the modulation transfer function as the standard deviation of image intensities in a region of interest is to:

A. contrast-detail image
B. detective quantum efficiency
C. noise equivalent quanta

D. noise power spectrum (Wiener spectrum)
E. signal-to-noise ratio

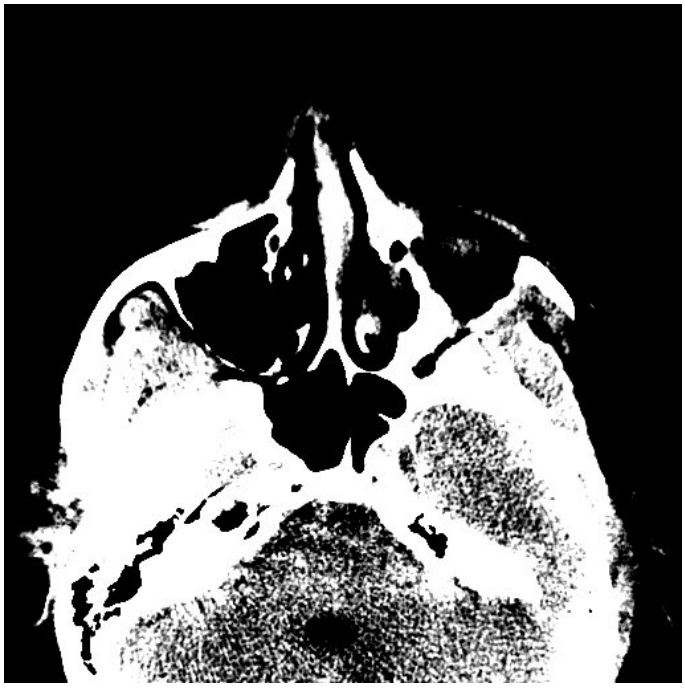
Answer: D – noise power spectrum (Wiener spectrum)

Explanation: Limiting resolution is a single number estimate of spatial resolution. The modulation transfer function is a more complete measurement of resolution as a function of spatial frequency. The standard deviation of image intensities is a single number estimate of image noise. The noise power spectrum is a more complete measurement of noise as a function of spatial frequency.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Boedeker, K.L., V.N. Cooper, M.F. McNitt-Gray. "Application of the noise power spectrum in modern diagnostic MDCT: part I. Measurement of noise power spectra and noise equivalent quanta." *Phys. Med. Biol.* 52:4027–4046, 2007.

Q3. The CT image shown below is viewed at a window width of 30 HU and level of 20 HU. What change should be made to make the image contrast of the brain tissues more visible?



A. increase window width
B. decrease window width
C. increase window level
D. decrease window level

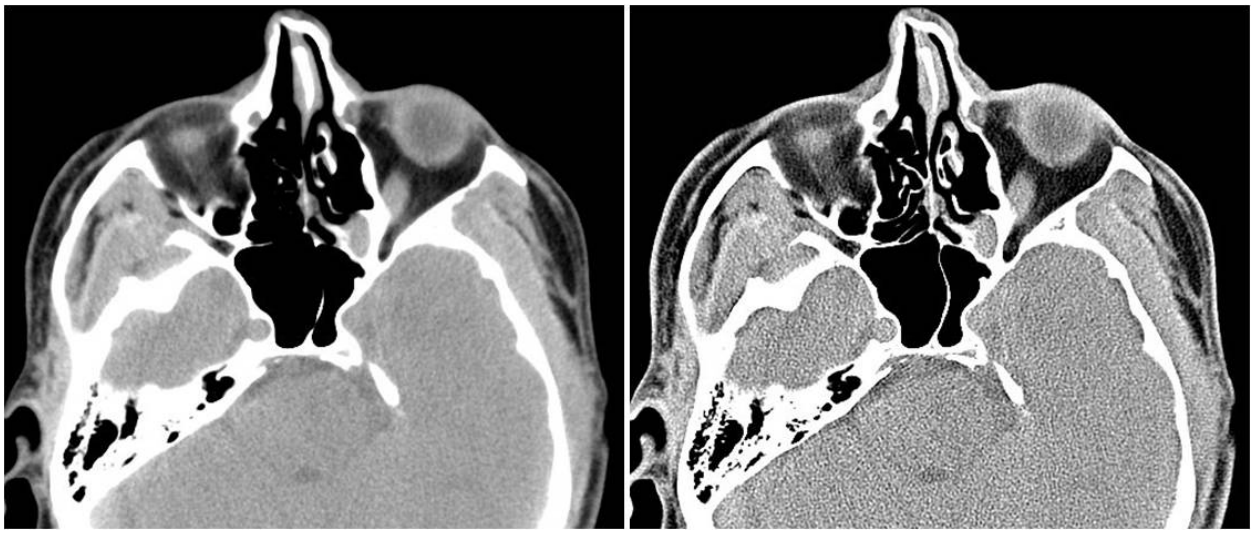
Answer: A – increase window width

Explanation: Soft tissue is 0–100 HU, air –1000 HU, and bone 500 HU–1500 HU. Currently the image is viewed with the center at 20 HU and a window width of 30 HU (i.e., 15 HU below and 15 HU above the 20 HU center). With this setting, it maps black to any pixel with a value less than 5 HU and white to any pixel with a value greater than 35 HU. This is a poor windowing 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). Increasing the window width will improve the contrast different soft tissues in the image.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Hendee, W.R. and E.R. Ritenour. *Medical Imaging Physics*, 4th ed. New York: Wiley–Liss, 2002.

Q4. What parameter change is the most likely cause of the increased noise and decreased resolution in the images below?



A. different kVp
B. different mAs
C. different gantry angle
D. different convolution kernel/filter

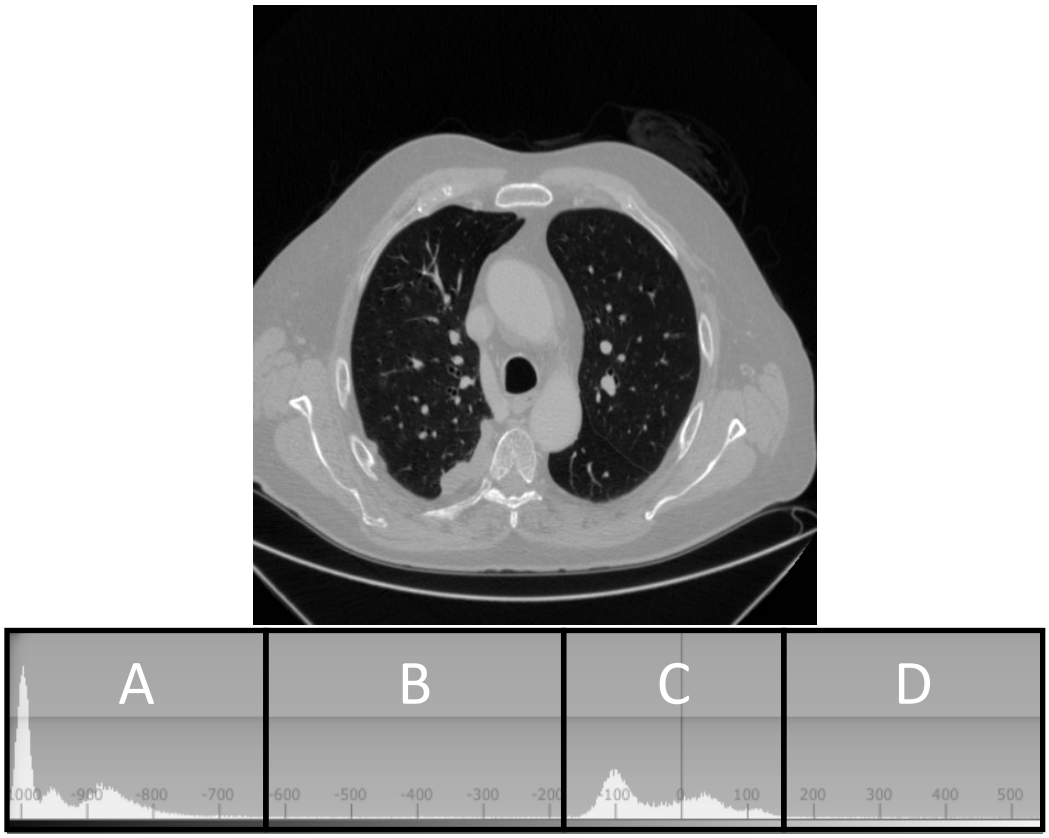
Answer: D – different convolution kernel/filter

Explanation: The image on the left is less noisy, but it also demonstrates a higher degree of blurring (lower resolution). Increasing kVp or mAs will decrease image noise; however, neither substantially changes spatial resolution. Changing the gantry angle would create oblique sections, but not impact image quality. Changing the convolution kernel (aka, convolution 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*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2010.

Q5. Which histogram region corresponds to soft tissue in the CT image shown below?



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

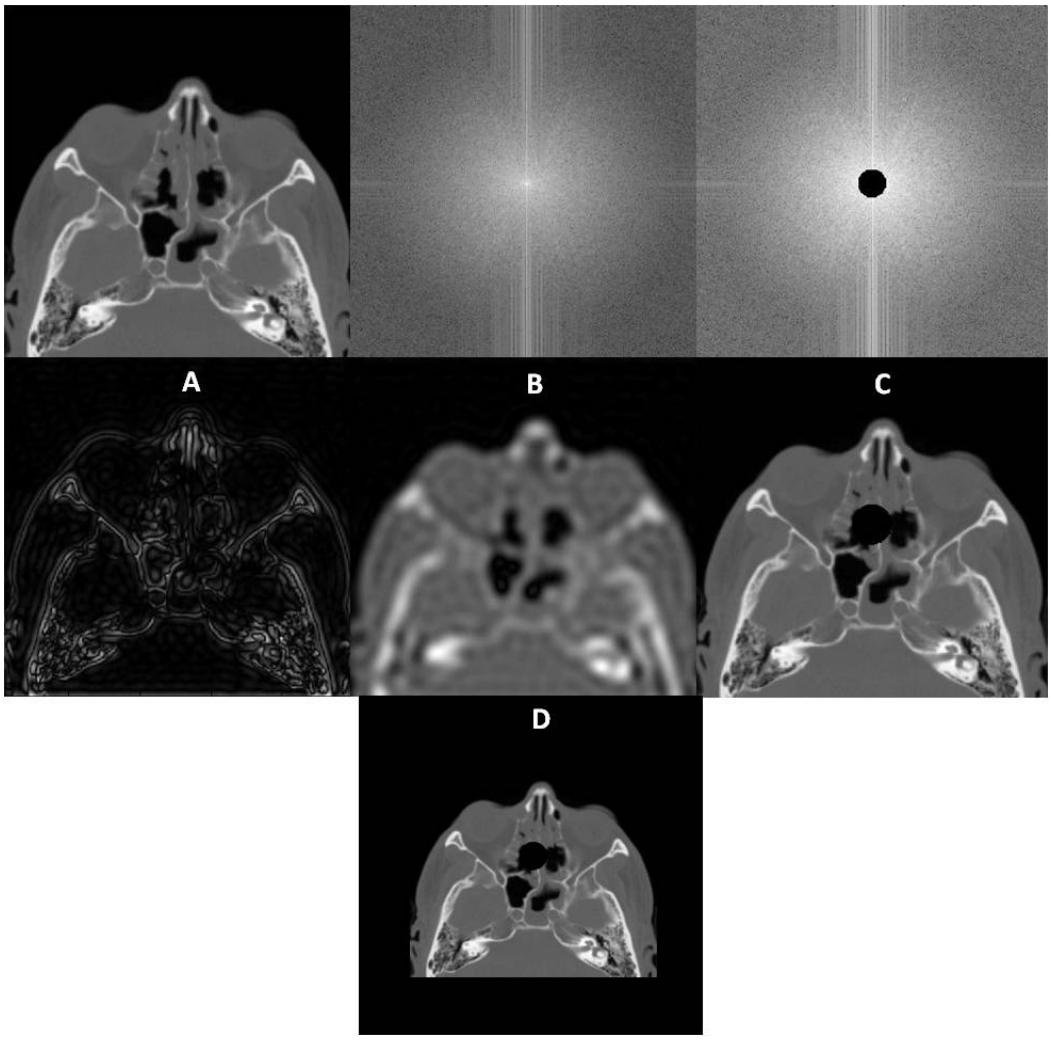
Answer: C

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). D (HU > 200) is mainly bone, and there are relatively few bone-valued pixels in the image. B (HU −500 to −200) is the region below fat, but above air, which has relatively few pixels. A (HU < −700) is mainly air and lung, which make up the majority of the image. C (HU −150 to 150) is the soft tissue — only air and lung have more pixels in this image.

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 images corresponds to altering the Fourier Transform as demonstrated in the top right figure?



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

Answer: A

Explanation: The top right figure illustrates the application of a high-pass filter which discards all low spatial frequencies in the Fourier Spectrum. Thus only edges are left in the image (A). 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 C reduced in size.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. Hendee, W.R. and E.R. Ritenour. *Medical Imaging Physics*, 4th ed. New York: Wiley–Liss, 2002.

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 which 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 which 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 which 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.

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

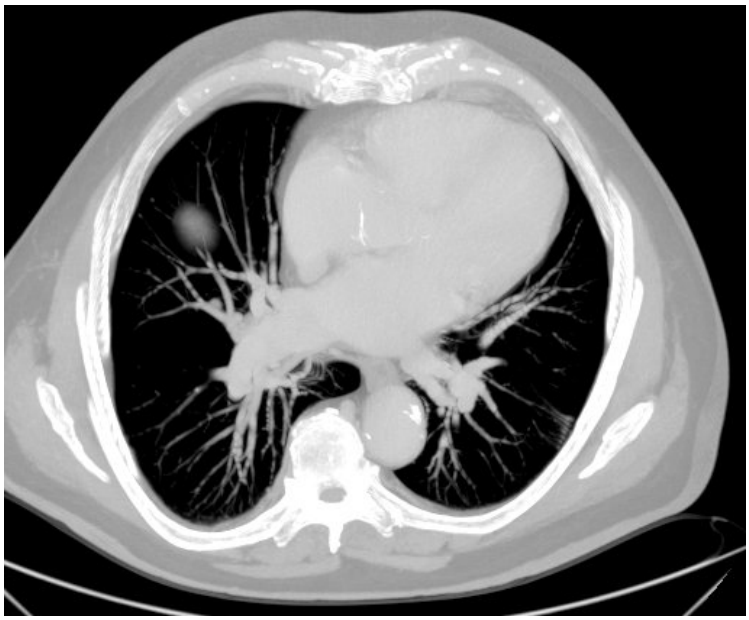
Answer: B – applying image smoothing

Explanation: A) Edge enhancement will increase noise and will likely make detection more difficult. C) Increasing window width will decrease the apparent noise, but it also decreases display contrast, making detection more difficult. D) 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 smoothes the image. B) Applying smoothing reduces noise without reducing contrast (since the object is large) thus improving detectability.

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 01/23/2012.

Q9. The CT image below is:



A. MIP
B. surface render
C. volume render
D. MPR
E. fused image

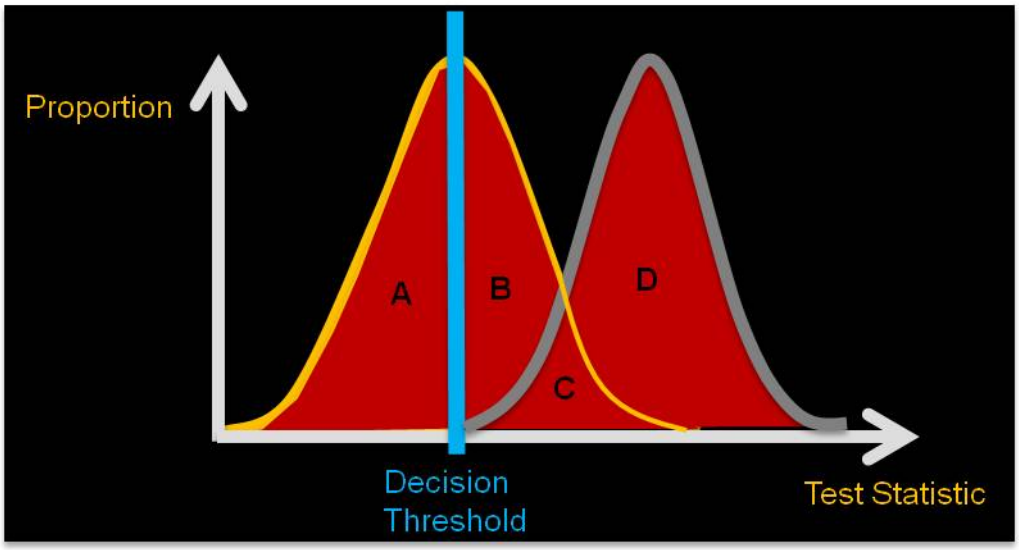
Answer: A – MIP

Explanation: B) A surface-rendered image shows a 3D rendering of one or several organ surfaces. C) 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. E) 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). A) 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.

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. The yellow curve represents the histogram of patients confirmed as normal, and the gray curve represents the histogram of patients that are diseased. The test decision threshold is displayed below in blue, and everything above the threshold is called disease by the new diagnostic test. Which region(s) contains true positive results?



A. A and B
B. B and C
C. C and D

Answer: C – C and D

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 8: Biological Effects of Ionizing Radiation

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Describe the cell cycle, and discuss the radiosensitivity of each phase.
2. Discuss the probability of cell survival for low-LET radiations.
3. Compare the radiosensitivities of different organs in the body.
4. Explain the effects of massive whole-body irradiation and how it is managed.
5. Understand the threshold for deterministic effects, including cutaneous radiation injury, cataracts, and sterility.
6. Explain the risk of carcinogenesis due to radiation.
7. Understand the latencies for different cancers.
8. Explain the effects of common drugs on radiation sensitivity.
9. Describe the effect of radiation on mutagenesis and teratogenesis.
10. List the most probable *in utero* radiation effects at different stages of gestation.
11. Define the principles of how radiation deposits energy that can cause biological effects.
12. Explain the difference between direct and indirect effects, how radiation affects DNA, and how radiation damage can be repaired.
13. Recognize the risk vs. benefit in radiation uses, and recognize the information sources that can be used to assist in assessing these risks.
14. Describe the different dose response models for radiation effects.

Clinical Application:

1. Understand the risks to patients from high-dose fluoroscopy regarding deterministic effects, such as cutaneous radiation injury and cataractogenesis, and the importance of applying radiation protection principles in clinical protocols to avoid damage.
2. Understand the risks to the female breast, especially in girls, from repeated imaging for scoliosis, from mobile chest radiography, and CT scans; and understand the importance of applying radiation protection principles in clinical protocols to minimize future harm.
3. Explain radiation risks to pregnant technologists assisting in fluoroscopic procedures.
4. Explain radiation risks to pregnant nurses who are incidentally exposed in mobile radiography ("portables").
5. Understand the best use of gonad shielding and breast shields.

Clinical Problem-solving:

1. Plan an interventional procedure to minimize the risk of deterministic effects.
2. Select the most appropriate radiological exam for a pregnant patient.
3. Determine the risk vs. benefit for a new procedure shown at a conference.

Concise Syllabus:

8.1. Principles of Radiation Biology
8.2. Molecular Effects of Radiation
8.3. Cellular Effects of Radiation
  8.3.1. Law of Bergonié and Tribondeau
  8.3.2. Radiosensitivities of Different Cell Types
  8.3.3. Radiosensitivities of Phases of the Cell Cycle

8.3.4. Cell Damage
8.3.5. Cell Survival Curves
8.3.6. Repair
8.4. System Effects of Radiation
8.5. Deterministic (Non-stochastic) Effects
8.5.1. Radiation Syndromes
8.5.2. Erythema
8.5.3. Epilation
8.5.4. Cataracts
8.5.5. Sterility
8.6. Probabilistic (Stochastic) Radiation Effects
8.6.1. Radiation Epidemiology: Case Studies
8.6.2. Carcinogenesis
8.6.3. Mutagenesis
8.6.4. Teratogenesis
8.7. Radiation Risk
8.8. Dose-response Models

Detailed Syllabus:

8. Radiation Biology
8.1. Principles
8.1.1. Linear Energy Transfer
8.1.2. Relative Biological Effectiveness
8.1.3. Weighting Factors
8.2. Molecular Effects of Radiation
8.2.1. Direct Effects
8.2.2. Indirect Effects
8.2.3. Effects of Radiation on DNA
8.3. Cellular Effects of Radiation
8.3.1. Law of Bergonié and Tribondeau
8.3.2. Radiosensitivity of Different Cell Types
8.3.3. Cell Cycle Radiosensitivity
8.3.4. Cell Damage
8.3.4.1. Division Delay
8.3.4.2. Mitotic Death
8.3.4.3. Apoptosis
8.3.5. Cell Survival Curves
8.3.6. Repair
8.4. System Effects of Radiation
8.4.1. Tissues
8.4.2. Organs
8.4.3. Whole Body
8.4.4. Population
8.4.5. Common Drugs
8.5. Deterministic (Non-stochastic) Effects
8.5.1. Radiation Syndromes
8.5.1.1. Prodromal
8.5.1.2. Hematopoetic

- 8.5.1.3. Gastrointestinal
- 8.5.1.4. Cerebrovascular and CNS
- 8.5.1.5. Sequence of Events
- 8.5.1.6. $LD_{50/60}$
- 8.5.1.7. Monitoring and Treatment

8.5.2. Other Effects

- 8.5.2.1. Erythema
- 8.5.2.2. Epilation
- 8.5.2.3. Cataracts
- 8.5.2.4. Sterility

8.6. Probabilistic (Stochastic) Radiation Effects

8.6.1. Radiation Epidemiology – Case Studies

8.6.2. Carcinogenesis

- 8.6.2.1. Radiation-induced Cancers
  - 8.6.2.1.1. Leukemia
  - 8.6.2.1.2. Solid Tumors
- 8.6.2.2. Spontaneous Rate
- 8.6.2.3. Latency

8.6.3. Mutagenesis

- 8.6.3.1. Baseline Mutation Rate
- 8.6.3.2. Doubling Dose

8.6.4. Teratogenesis

- 8.6.4.1. Developmental Effects
- 8.6.4.2. Childhood Leukemia
- 8.6.4.3. Gestational Sensitivity

8.7. Radiation Risk

8.7.1. Risk–Benefit in Radiology

8.7.2. Risk Models

- 8.7.2.1. Relative
- 8.7.2.2. Absolute

8.7.3. Information Sources

- 8.7.3.1. Biological Effects of Ionizing Radiation Reports (e.g., BEIR VII)
- 8.7.3.2. International Council on Radiation Protection (ICRP)
- 8.7.3.3. National Council on Radiation Protection (e.g., NCRP 116)
- 8.7.3.4. United Nations Scientific Committee on the Effects of Atomic Radiation Reports (UNSCEAR)

8.7.4. Perception of Risk

- 8.7.4.1. Compare Radiation Risk with Smoking, Drinking, Driving, etc.

8.8. Dose-response Models

8.8.1. Linear, No-threshold (LNT)

8.8.2. Linear-quadratic

8.8.3. Radiation Hormesis

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. The energy deposition of an alpha particle is much higher per unit path length than gamma rays, x-rays, or a beta particle.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 36.
2. Hall, E.J. and A.M. Giaccia. *Radiobiology for the Radiologist*, 7th ed. Philadelphia: Lipincott William & Wilkins, 2011.

Q2. Radiation-related factors that determine the biological effects of radiation include all but one of the following:

A. absorbed dose
B. dose rate
C. DNA repair mechanisms
D. type and energy of radiation

Answer: C – DNA repair mechanisms

Explanation: The biological effect of DNA repair mechanisms are not related to the radiation used, but to the tissue that is being irradiated.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 751.
2. Hall, E.J. and A.M. Giaccia. *Radiobiology for the Radiologist*, 7th ed. Philadelphia: Lipincott William & Wilkins, 2011.

Q3. What cell type is most sensitive to radiation injury?

A. erythroblast
B. erythrocyte
C. myocyte
D. hepatocyte

Answer: A – erythroblast

Explanation: Erythroblasts, compared to the other cell types, are rapidly dividing cells that spend more time in the M phase of the cell cycle, which is most vulnerable to radiation injury.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 770.
2. Hall, E.J. and A.M. Giaccia. *Radiobiology for the Radiologist*, 7th ed. Philadelphia: Lipincott William & Wilkins, 2011.

Q4. What molecule is the primary site of radiation-induced injury?

A. deoxyribonucleic acid
B. ribonucleic acid
C. DNA polymerase
D. hemoglobin

Answer: A – deoxyribonucleic acid

Explanation: There is strong evidence that the principle target for the biologic effects of radiation—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, p. 757–759.
2. Hall, E.J. and A.M. Giaccia. *Radiobiology for the Radiologist*, 7th ed. Philadelphia: Lipincott William & Wilkins, 2011, p. 12–16.

Q5. Which of the following is a non-deterministic (stochastic) biologic effect of radiation?

A. hair loss
B. skin erythema
C. cataract
D. risk of cancer

Answer: D – risk of cancer

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

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: Lipincott William & Wilkins, 2011.

Q6. What would be a lethal dose of whole body radiation?

A. 10 Gray
B. 1 Gray
C. 0.1 Gray
D. 0.01 Gray

Answer: A – 10 Gray

Explanation: 10 Gray of absorbed whole body radiation is considered a lethal dose of radiation essentially 100% of the time with or without treatment.

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: Lipincott William & Wilkins, 2011.

Q7. A pulmonary CT angiogram to assess the presence of pulmonary emboli in a 28-year-old woman who was 30 weeks pregnant would most likely increase the risk to the fetus of which of the following:

A. fetal malformation
B. prenatal death
C. childhood cancer
D. cataracts

Answer: C – childhood cancer

Explanation: At 30 weeks of pregnancy the woman is well into the third trimester, and the risk to the fetus from low levels of radiation would be some increased risk for childhood cancers.

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: Lipincott William & Wilkins, 2011.

Q8. What is the most radiosensitive organ in a young adult woman 24 years of age?

A. breast
B. lung
C. ovary
D. skin

Answer: A – breast

Explanation: Breast tissue is the most radiosensitive organ in female children and young adult women.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 816.
2. Hall, E.J. and A.M. Giaccia. *Radiobiology for the Radiologist*, 7th ed. Philadelphia: Lipincott William & Wilkins, 2011.

Q9. What dose-response model does the BEIR VII report recommend for calculating the risk of biologic effects from ionizing radiation?

A. linear-quadratic
B. linear, threshold
C. linear, no threshold
D. radiation hormesis

Answer: C – linear no threshold

Explanation: The BEIR VII report uses the no threshold linear dose response model.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 806–808.
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.

Q10. What percentage of excess cases of cancer would you expect in a general population in the USA if 10,000 people were exposed to 10 mSv over one year from a slow radiation leak?

A. <30 percent
B. <3 percent
C. <0.3 percent
D. <0.03 percent

Answer: C – <0.3 percent

Explanation: The U.S. population's average radiation-induced cancer incidence is 11.4% per Sv. [10,000 × 10 mSv] × .114/Sv = 10^5 mSv × [11.4×10^{-5}/mSv] = 11.4/10000 = 0.114%, or <0.3%.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 812–815.
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.

Module 9: Radiation Protection and Associated Regulations

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Identify the sources of background radiation, and describe the magnitude of each source.
2. State the radiation limits to the public and radiation workers (maximum permissible dose equivalent limits).
3. Understand the differences among 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, and shielding 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 areas of possible exposure or contamination.
8. Describe the fundamental methods used to determine patient and fetal doses.
9. Explain the basic principles for designing radiation shielding.
10. List the steps in managing radiological emergencies.

Clinical Application:

1. Understand the safety considerations for patients and staff, including pregnant staff, in mobile radiography ("portables").
2. Use your knowledge of radiation effects in planning for and reacting to an emergency that includes the exposure of personnel to radiation.
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 the radiation safety officer.
5. Describe the training and experience requirements for using sealed and unsealed sources of radioactive material.
6. Describe the use of personnel radiation protection equipment.
7. Describe the appropriate equipment for wipe tests and contamination surveys.
8. Provide information to the public concerning radon.
9. Provide clinical examples that demonstrate ALARA principles.
10. Discriminate between workers in an area who are occupationally exposed and those who are treated as members of the general public.

Clinical Problem-solving:

1. Discuss the factors that determine dose to a pregnant person seated next to a patient injected with a radionuclide for a diagnostic or therapeutic procedure.
2. Describe the steps used in applying appropriateness criteria.
3. Describe what must be done before administering a radioactive material in a patient.
4. Describe what is required to have a person listed on a facility's nuclear materials license as an authorized user.

Concise Syllabus:

9. Radiation Protection and Associated Regulations

9.1. Background Radiation
9.2. Non-medical Sources
9.3. Medical Sources
    9.3.1. JCAHO Sentinel Event
9.4. Persons at Risk
9.5. Dose Limits
9.6. Personnel Dosimetry
9.7. Radiation Detectors
9.8. Principles of Radiation Protection
    9.8.1. Time
    9.8.2. Distance
    9.8.3. Shielding
    9.8.4. Contamination Control
    9.8.5. As Low as Reasonably Achievable (ALARA)
    9.8.6. Culture of Safety
9.9. Factors Affecting Patient Dose
    9.9.1. Radiography
    9.9.2. Fluoroscopy and Interventional Radiology
    9.9.3. Computed Tomography (CT)
    9.9.4. Mammography
    9.9.5. Nuclear Medicine
9.10. Advisory Bodies
9.11. Regulatory Agencies
9.12. Radiation Safety in the Use of Radioactive Materials
    9.12.1. Surveys
    9.12.2. Ordering, Receiving, and Unpacking Radioactive Materials
    9.12.3. Contamination Control
    9.12.4. Radioactive Waste Management
    9.12.5. Reportable Events
9.13. Estimating Patient, Pediatric and Fetal Dose (Procedure-specific Doses)
9.14. Shielding
9.15. Radiological Emergencies

Detailed Curriculum:

9. Radiation Protection and Associated Regulations
    9.1. Background Radiation
        9.1.1. Cosmic
        9.1.2. Terrestrial
        9.1.3. Internal
        9.1.4. Radon
    9.2. Non-medical Sources
        9.2.1. Nuclear Power Emissions
        9.2.2. Tobacco
        9.2.3. Technologically Enhanced Naturally Occurring Radioactive Material (TENORM)
        9.2.4. Fallout
    9.3. Medical Sources: Occupational and Patient Doses
        9.3.1. Projection Radiography

9.3.2. Mammography
9.3.3. Fluoroscopy
9.3.4. Interventional Radiology and Diagnostic Angiography
9.3.5. CT
9.3.6. Sealed Source Radioactive Material
9.3.7. Unsealed Radioactive Material
9.3.8. Therapeutic External Radiation
9.3.9. Non-ionizing

9.4. Factors Affecting Patient Dose
9.4.1. Radiography
9.4.2. Fluoroscopy and Interventional Radiology
9.4.3. Computed Tomography (CT)
9.4.4. Mammography
9.4.5. Nuclear Medicine
9.4.6. Regulatory Dose Limits and "Trigger" Levels
9.4.6.1. Institutional
9.4.6.2. Local
9.4.6.3. State
9.4.6.4. Federal
9.4.7. JCAHO Reviewable and Non-reviewable Events
9.4.7.1. Person or Agency to Receive Report

9.5. Persons at Risk
9.5.1. Occupational
9.5.2. Non-occupational Staff
9.5.3. Members of the Public
9.5.4. Fetus
9.5.5. Patient
9.5.5.1. Adult
9.5.5.2. Child
9.5.5.3. Pregnancy Identified
9.5.5.4. Pregnancy Status Unknown

9.6. Dose limits
9.6.1. Occupational Dose Limits
9.6.1.1. Effective Dose
9.6.1.2. Specific Organ
9.6.1.3. Pregnant Workers
9.6.2. Members of the Public
9.6.2.1. General
9.6.2.2. Caregivers
9.6.2.3. Limit to Minors

9.7. Radiation Detectors
9.7.1. Personnel Dosimeters
9.7.1.1. Film
9.7.1.2. Thermoluminescent Dosimeters (TLDs)
9.7.1.3. Optically-stimulated Luminescent (OSL) Dosimeters
9.7.1.4. Electronic Personnel Dosimeters
9.7.1.5. Applications: Appropriate Use and Wearing
9.7.1.6. Limitations and Challenges in Use

9.7.2. Area Monitors
9.7.2.1. Dosimeters
9.7.2.2. Ion Chambers
9.7.2.3. Geiger–Müeller (GM)
9.7.2.4. Scintillators
9.8. Principles of Radiation Protection
9.8.1. Time
9.8.2. Distance
9.8.3. Shielding
9.8.3.1. Facility
9.8.3.2. Workers
9.8.3.3. Caregivers
9.8.3.4. Patients
9.8.3.5. Members of the Public
9.8.3.6. Appropriate Materials
9.8.4. Contamination Control
9.8.5. As Low as Reasonably Achievable (ALARA)
9.8.5.1. Culture of Safety
9.8.5.2. "Open Door" Policy
9.8.6. Procedure Appropriateness
9.9. Advisory Bodies
9.9.1.1. International Commission on Radiological Protection (ICRP)
9.9.1.2. National Council on Radiation Protection and Measurements (NCRP)
9.9.1.3. Conference of Radiation Control Program Directors (CRCPD)
9.9.1.4. International Atomic Energy Agency (IAEA)
9.9.1.5. Joint Commission on Accreditation of Healthcare Organizations (JC)
9.9.1.6. American College of Radiology (ACR)
9.9.1.7. National Electrical Manufacturers Association (NEMA) (Medical Imaging and Technology Alliance or MITA)
9.10. Regulatory Agencies
9.10.1. U.S. Nuclear Regulatory Commission and Agreement States
9.10.1.1. 10 CFR Parts 19, 20, 30, 32, 35, 110
9.10.1.2. Guidance Documents (NUREG 1556, Vols. 9 & 11)
9.10.1.3. Regulatory Guides
9.10.2. States: for Machine-produced Sources
9.10.2.1. Suggested State Regulations
9.10.3. U.S. Food and Drug Administration
9.10.3.1. Center for Devices and Radiological Health (CDRH)
9.10.3.2. Center for Drug Evaluation and Research (CDER)
9.10.4. U.S. Office of Human Research Protections
9.10.5. U.S. Department of Transportation
9.10.5.1. U.S. Department of Labor (OSHA)
9.10.6. International ElectroTechnical Commission (IEC)

9.11. Radiation Safety with Radioactive Materials
9.11.1. Surveys
9.11.1.1. Area
9.11.1.2. Wipe Test

9.11.1.3. Spills
9.11.2. Ordering, Receiving, and Unpacking Radioactive Materials
9.11.3. Contamination Control
9.11.4. Radioactive Waste Management
9.11.5. Qualifications for Using Radioactive Materials
9.11.5.1. Diagnostic (10 CFR 35.200 and 35.100, or Equivalent Agreement State Regulations)
9.11.5.2. Therapeutic (10 CFR 35.300 and 35.1000, or Equivalent Agreement State Regulations)
9.11.6. Medical Events
9.11.6.1. Reportable
9.11.6.2. Non-reportable
9.11.6.3. Person or Agency to Receive Report
9.11.7. Special Considerations
9.11.7.1. Pregnant Patients
9.11.7.2. Breast-feeding Patients
9.11.7.3. Caregivers
9.11.7.4. Patient Release
9.12. Estimating Effective Fetal Dose (Procedure-specific Doses)
9.12.1. Radiography
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9.12.3. Fluoroscopy
9.12.4. Computed Tomography (CT)
9.12.5. Nuclear Medicine

9.13. Shielding
9.13.1. Design Philosophy
9.13.1.1. Occupancy
9.13.1.2. Workload
9.13.2. Controlled vs. Uncontrolled Areas
9.13.3. Examples of Shielding Design
9.13.3.1. Diagnostic X-Ray Room
9.13.3.2. PET Facility
9.13.3.3. Hot Lab and Nuclear Medicine Facility
9.14. Radiological Emergencies
9.14.1. Incidents
9.14.1.1. Nuclear Power
9.14.1.2. Military Equipment
9.14.1.3. Transportation Accidents
9.14.1.4. Research Lab and Radiopharmacy Accidents
9.14.2. Purposeful Exposures
9.14.2.1. Nuclear Detonation
9.14.2.2. Radiological Dispersion Device (RDD)
9.14.2.3. Environmental Contamination
9.14.2.4. Radiological Exposure Device (RED)
9.14.3. Treatment of Radiological Casualties
9.14.3.1. Notification and Patient Arrival
9.14.3.2. Triage: Evaluation, Dispensation, and Initial Treatment

9.14.3.3. External Exposure and Internal Contamination
9.14.3.4. Radiological Assessment
9.14.3.5. Medical Management
9.14.3.6. Oak Ridge Radiation Emergency Assistance Center

Example Q&A:

Q1. The recommended weekly effective dose limit for radiologists under current regulations is:

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

Answer: E – 1.0 mSv

Explanation: The YEARLY annual effective dose limit for occupational workers is 50 mSv. Assuming 50 weeks a year, the approximate WEEKLY effective dose limit is 1 mSv.

Reference:

1. Table 23-10. Nuclear Regulatory Commission (NRC) Regulatory Requirements: Maximum Permissible Dose Equivalent Limits. In Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed.. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q2. According to NCRP Reports 93 (1987) and 160 (2009), over time the yearly level of background/ natural radiation received per capita has most nearly:

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. According to NCRP reports 93 (1987) and 160 (2009), the effective dose received by the average American from Medical radiation has, over time, most nearly:

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: C – increased by a factor of six

Explanation: In NCRP Report 93 (1987), the medical contribution (listed as medical x-rays and nuclear medicine) was reported as 0.5 mSv per year. By 2009, the NCRP listed medical contributions into four categories: computed tomography, interventional fluoroscopy, conventional radiography/fluoroscopy, and nuclear medicine. The total contribution was estimated at 3.0 mSv per capita per year in NCRP Report 160 (2009), a six-fold increase from 0.5 mSv per year.

References:

1. NCRP Report 93 (1987)
2. NCRP Report 160 (2009)

Q4. For a janitor's closet adjacent to a radiographic room, the shielding calculation design goal is:

A. 50 mSv per year
B. 1 mSv per week
C. 0.02 mSv per week
D. 0.1 mSv per week

Answer: C – 0.02 mSv per week

Explanation: The closet is an uncontrolled area, thus the exposure should meet the annual permissible limit for a member of the general public. The NRC Regulatory Requirement for individual members of the public is 1.0 mSv per year; with 52 weeks in a year, the shielding design goal is 1.0 mSv per year divided by 52 weeks per year, or 0.02 mSv per week. This limit is also explicitly stated in NCRP Report 147.

References:

1. Table 23-10. Nuclear Regulatory Commission (NRC) Regulatory Requirements: Maximum Permissible Dose Equivalent Limits. In Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed.. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. National Council on Radiation Protection & Measurements. *NCRP Report 147 – Structural Shielding Design for Medical X-ray Imaging Facilities.* Bethesda, MD: NCRP, 2004.

Q5. The ICRP released a statement in 2011 stating that the dose threshold for radiation-induced cataracts was <u>(increased/ decreased)</u> from 2 Gy to _____.

A. increased, 3 Gy
B. increased, 4 Gy
C. increased, 8 Gy
D. decreased, 0.5 Gy
E. decreased, 0.5 mGy

Answer: D – decreased, 0.5 Gy

Explanation: The ICRP recently released a new recommendation to change the occupational limit for the lens of the eye based on the IAEA Retrospective Evaluation of Lens Injury and Dose (RELID). Until recently, it was understood that the dose threshold required to produce a radiation-induced cataract was high (>2 Gy). Based on the IAEA studies of patients and occupational workers, the International Commission on Radiological Protection (ICRP) released a statement indicating lens opacities occur at doses of 0.5 Gy.

Reference:

1. International Commission On Radiological Protection. "ICRP Statement on Tissue Reactions." ICRP ref 4825-3093-1464. Available at http://www.icrp.org/page.asp?id=123.

Q6. The following organizations or agencies are *regulatory* bodies that oversee the use of x-rays in medical imaging:

1. U.S. Nuclear Regulatory Commission (NRC)
2. Food and Drug Administration (FDA)
3. National Council on Radiation Protection and Measurement (NCRP)
4. U.S. Department of Transportation (DOT)

A. 1 only
B. 1 and 2
C. 1, 2, and 3
D. 1, 2, and 4
E. all of these are regulatory bodies

Answer: D – 1 (NRC), 2 (FDA), and 4 (DOT)

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.
- **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.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, Chapter 21, 2012.

Q7. As reported in NRCP Report 160, which category contributes the highest percentage to the total annual dose per capita?

A. computed tomography
B. nuclear medicine
C. radon
D. cosmic
E. medical

Answer: E – 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 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.

Reference:

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

Q8. Which of the following information is not needed to estimate the required shielding for a new x-ray room?

1. Which orientations the x-ray tube head can be placed in.
2. How many patients are seen in the x-ray clinic per week.
3. What types of exams are primarily done in that imaging suite.
4. The floor plans for the building design.
5. The number of people per week walking down the hallway adjacent to the x-ray suite.

A. #5 only
B. #3 only
C. #3 and #4
D. #4 and #5
E. all of this information is needed for shielding design

Answer: A – #5 only

Explanation: It is assumed that that hallway will not have the same person standing in the hallway all day, every day; shielding design evaluates the occupancy of any adjacent spaces for a given individual, not for the total number of individuals in that space for a given work week. Even though this is an uncontrolled area where members of the general public (with annual dose limit of 1 mSv per year) could be standing/walking, it is unlikely that any *specific* member of the public will stand adjacent to the x-ray room 100% of the work week. The hallway is assigned a fractional occupancy based on the fact that it is a hallway, not based on how heavily trafficked the hallway is. The tube orientation must be known so primary barriers and secondary only (scatter/leakage only) barriers can be identified.

The workload for an exam room is determined by the number of patients per week and by which types of exams are done in that room (#2 and #3). The operating potential (kVp) distribution of the workload must be determined for shielding evaluation (e.g., understanding the distribution of the fraction of chest examinations with *120 kVp* on the *wall stand* vs. *80 kVp* abdomen examination on the *table bucky*).

Floor plans for the rooms adjacent to the x-ray suite, as well as in the rooms on the floors above and below, should also be obtained so appropriate occupancy factors and shielding design goals can be assigned to all the rooms adjacent to the walls, floor, and ceiling of the imaging suite.

Reference:

1. National Council on Radiation Protection & Measurements. *NCRP Report 147 – Structural Shielding Design for Medical X-ray Imaging Facilities.* Bethesda, MD: NCRP, 2004.

Q9. What is the maximum permissible fluoroscopic exposure rate (normal mode) for an overhead tube configuration (e.g., urology imaging suite or multi-purpose R/F suite), and at what point is the exposure rate measured according to the Code of Federal Regulations (CFR)?

A. 10 R per minute, measured at the output window of the x-ray tube
B. 10 R per minute, measured at the entrance position of the patient (30 cm above the table top)
C. 10 R per minute, measured at the exit position of the patient (1 cm above the table top)
D. 20 R per minute, measured at the output window of the x-ray tube
E. 20 R per minute, measured at the entrance position of the patient (30 cm above the table top)

Answer: B – 10 R per min, measured at the entrance position of the patient (30 cm above the table top)

Explanation: The maximum permissible exposure rate for the fluoroscopy output is 10 R per minute and 20 R per minute for "specially activated" or "high-level" fluoroscopy (HLF). Generally, the exposure rate should be measured at the point where the incident radiation is entering the patient (entrance skin dose position). The accepted patient thickness in the AP direction is roughly 30 cm; hence, for an overhead tube configuration, the measurement point should be 30 cm above the table top in the direction of the x-ray tube.

Reference:

1. Code of Federal Regulation (CFR) Title 21 (21CFR1020.32).

Q10. The radiation badge typically worn by a radiologist is likely a/an

A. ionization chamber
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 dosimeter, usually used for ring badges). The most common badge is an OSL (e.g., Landauer badges).

Typically, personnel monitors are *passive* detectors (though not always) because the information is stored by the monitor and read out later. *Active* detectors are effectively "real-time" detectors (e.g., ionization chambers or Geiger-Müller survey meters).

Ionization chambers are typically used by physicists to measure radiation output intensity.

Scintillation detectors are typically used in imaging systems to convert incident photons into light (e.g., scintillation crystal on a gamma camera). They are also commonly used in probes for non-imaging exams such as thyroid uptake; in well counters for package, area survey, and contamination sample counting; and in survey meters for contamination and shielding evaluations.

GM detectors are typically used as survey meters to measure low levels of radiation, such as contamination in a radiopharmacy.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, Chapter 21, 2012.

Module 10: X-Ray Projection Imaging Concepts and Detectors

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Describe the fundamental characteristics of all projection imaging systems that determine the capabilities and limitations in producing an x-ray image.
2. Review the detector types used to acquire an x-ray imaging. Describe how radiation is detected by each detector type and the different attributes of each detector for recording information.

Clinical Application:

1. Demonstrate how variations in each of the fundamental characteristics of a projection imaging system affect the detected information in producing an image.
2. Give examples of how each detector type performs in imaging a specific body part or view, and describe how the attributes of each detector type influence the resulting image.

Clinical Problem-solving:

1. What is the difference in exposure class between CR and DR systems? How does this difference affect patient dose?
2. Describe some of the common artifacts seen in a portable chest x-ray images, and explain how these can be minimized.
3. Describe how distance to the patient and detectors affect patient dose.
4. Describe how the transition from film to digital detector systems has eliminated some artifacts and created the possibility of others.
5. What are the properties of a detector system that determines its suitability for pediatric procedures?

Concise Syllabus:

10. X-ray Projection Imaging Concepts and Detectors
    - 10.1. Radiography Concepts
        - 10.1.1. Geometry
        - 10.1.2. Radiographic Contrast
        - 10.1.3. Scatter and Scatter Reduction
        - 10.1.4. Artifacts and Image Degradation
    - 10.2. Radiographic Detectors
        - 10.2.1. Intensifying Screen and Film
        - 10.2.2. Computed Radiography (CR)
        - 10.2.3. Direct Digital Radiography (DR)
        - 10.2.4. Indirect Digital Radiography (DR)

Detailed Curriculum:

10. X-ray Projection Imaging Concepts and Detectors
    - 10.2.1. Radiography Concepts
    - 10.2.2. Geometry
        - 10.2.2.1. Source-to-image Receptor Distance (SID), Source-to-object Distance (SOD), and Object-to-image Receptor Distance (OID)
        - 10.2.2.2. Magnification

10.2.2.3. Inverse-square Law
10.2.3. Radiographic Contrast
10.2.3.1. Subject
10.2.3.2. Object
10.2.3.3. Detector
10.2.4. Scatter and Scatter Reduction
10.2.4.1. Scatter-to-primary Ratio
10.2.4.2. Scatter Fraction
10.2.4.3. Collimation
10.2.4.4. Anti-scatter Grids
10.2.4.5. Air Gap
10.2.5. Artifacts and Image Degradation
10.2.5.1. Geometrical Distortion
10.2.5.2. Focal Spot: Blur and Penumbra
10.2.5.3. Grid: Artifacts and Cutoff
10.2.5.4. Motion
10.2.5.5. Superposition
10.3. Radiographic Detectors
10.3.1. Intensifying Screen and Film
10.3.1.1. Phosphors
10.3.1.2. Film
10.3.1.3. Screen/Film Systems
10.3.1.4. Latent Image Formation
10.3.1.5. Chemical Processing
10.3.1.6. Characteristic Curve
10.3.1.7. Spatial and Contrast Resolution
10.3.1.8. Artifacts
10.3.2. Computed Radiography (CR)
10.3.2.1. Storage Phosphors
10.3.2.2. Latent Image Formation
10.3.2.3. Image Digitization
10.3.2.4. Pre-processing (e.g., Gain and Bad Pixel Correction)
10.3.2.5. Imaging Characteristics
10.3.2.6. Artifacts
10.3.3. Direct Digital Radiography (DR)
10.3.3.1. Semiconductor and Thin-film Transistor
10.3.3.2. Image Formation and Readout
10.3.3.3. Pre-processing (e.g., Gain and Bad Pixel Correction)
10.3.3.4. Imaging Characteristics
10.3.3.5. Artifacts
10.3.4. Indirect Digital Radiography (DR)
10.3.4.1. Phosphor, Photodiodes, and Thin-film Transistor
10.3.4.2. Image Formation and Readout
10.3.4.3. Pre-processing (e.g., Gain and Bad Pixel Correction)
10.3.4.4. Imaging Characteristics
10.3.4.5. Artifacts

Example Q&A:

Q1. Which of the following exams would most likely be performed without the use of a grid?

A. PA chest
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 kVp, field size, and patient thickness. Of the exams listed, the AP wrist would involve the lowest kVp, 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, p. 230–235.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008, p. 224–228.

Q2. Which of the following detectors is used in direct digital radiography?

A. gadolinium oxysulfide
B. cesium Iodide
C. barium fluorohalide
D. amorphous selenium

Answer: D – amorphous selenium

Explanation: Direct digital detectors convert x-rays directly to electrons. Gadolinium oxysulfide, cesium iodide, and barium fluorohalide are phosphors which emit light in response to x-ray absorption.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 207–222.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008, p. 412–434.

Q3. In order to minimize the effect of geometric blur on a radiographic image you would:

A. set the highest mA and shortest exposure time available
B. select the small focal spot
C. chose the detector with the smallest available pixel size
D. utilize immobilization devices

Answer: B – select the 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, p. 208.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008, p. 288–289.

Q4. Determine the actual size of an object if the image of the object measures 10 mm and the object is located half way between the x-ray tube target and the image receptor.

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, p. 207–208.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008, p. 285.

Q5. A portable x-ray is taken with a CR cassette with an 8:1 grid. The cassette is off-level from perpendicular to the x-ray tube. The resulting image will appear:

A. blurry
B. grainy
C. dark in the center
D. too light all over

Answer: B – grainy

Explanation: An off-level grid will result in uniform cutoff of primary (unscattered) x-rays across the image surface. The reduction in exposure to the CR cassette will increase the relative noise in the image.
References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 172.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008, p.239.

Q6. If the distance from the x-ray tube to the image receptor is changed from 72" to 40", which of the following will occur?

A. radiation dose to the patient will decrease by a factor of 4
B. image spatial resolution will increase
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, p. 207–208.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008, p.285.

Q7. An increase in which of the following factors will increase image contrast?

A. kVp
B. Filtration
C. SID
D. mAs

Answer: D – mAs

Explanation: Increasing the mAs results in the production of more photons, which results in less image noise. Noise adversely affects contrast.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012. p. 85–94 and p. 223–224.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008, p. 454–457.

Q8. Which of the following will improve low-contrast resolution in a radiographic image?

A. change from a 10:1 to an 8:1 grid
B. move the patient closer to the image receptor
C. reduce mAs
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. As scatter in the image decreases, low-contrast resolution increases.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 230–235.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008, p. 224–228.

Q9. When the absorption efficiency in the phosphor layer of an x-ray detector is increased by making the phosphor layer thicker, which of the following occurs?

A. spatial resolution decreases
B. noise increases
C. contrast resolution decreases
D. patient dose increases

Answer: A – spatial resolution decreases

Explanation: Phosphors absorb x-ray energy and convert it to visible light. Once the light is generated it spreads out. The thicker the phosphor layer is, the more spreading out of light (the signal) occurs, which reduces spatial resolution.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 225–226.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008, p. 210–214.

Q10. Which of the following uses a storage phosphor to capture the x-ray signal?

A. indirect DR
B. direct DR
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, p. 214–216.
2. Bushong, S.C. *Radiologic Science for Technologists*, 9th ed. St. Louis: Mosby Elsevier, 2008, p. 413–425.

Module 11: General Radiography

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Describe the components of a radiographic imaging system.
2. List and describe the factors affecting radiographic image quality.
3. Explain how the geometric features of a general radiographic system affect the resulting image.
4. Describe the different types of acquisition systems used in general radiography.
5. Distinguish among the basic imaging requirements for specific body part or views acquired in general radiography.
6. Define entrance skin exposure and how it relates to patient dose.

Clinical Application:

1. Give examples of appropriate technique factors used in common radiographic procedures.
2. Differentiate among the imaging acquisition parameters used in various clinical applications.
3. Why is image quality frequently compromised in mobile radiography?

Clinical Problem-solving:

1. Specify the geometric requirements for image acquisition that affect image quality.
2. List the system components that affect patient radiation dose, and describe how to reduce patient dose.
3. Analyze the radiation dose from a medical procedure, and communicate the benefits and risks to the referring physician.
4. Which factors determine the appropriate grid to use for different radiographic exams?

Concise Syllabus:

11. General Radiography
    - 11.1. X-ray System Components
    - 11.2. Geometrical Requirements
    - 11.3. Acquisition System Types
        - 11.3.1. Screen/Film
        - 11.3.2. Digital
        - 11.3.3. Dual-energy
        - 11.3.4. Linear Tomography
        - 11.3.5. Tomosynthesis
    - 11.4. Image Characteristics
    - 11.5. Application Requirements
        - 11.5.1. Chest
        - 11.5.2. Abdomen
        - 11.5.3. Spine
        - 11.5.4. Extremities
        - 11.5.5. Pediatrics and Neonatal
        - 11.5.6. Portable/Mobile
    - 11.6. Dosimetry
        - 11.6.1. Entrance Skin Exposure

11.6.2. Effective Dose
11.6.3. Doses for Different Procedures
11.6.4. Factors Affecting Patient Dose
11.7. Quality Control (QC) Tests and Frequencies

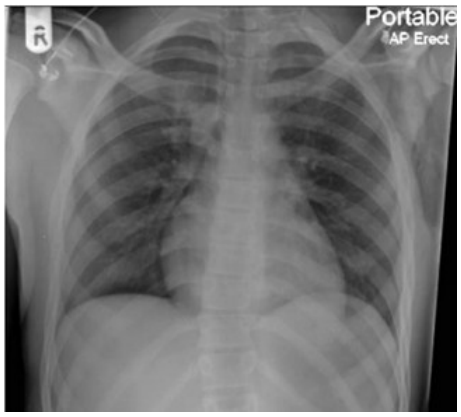
Detailed Curriculum:

11. General Radiography
    11.1. System Components
        11.1.1. Tube
        11.1.2. Filtration
        11.1.3. Collimation
        11.1.4. Automatic Exposure Control (AEC)
        11.1.5. Grid and Bucky Factor
        11.1.6. Compensation Filters
    11.2. Geometrical Requirements
        11.2.1. Focal Spot Size
        11.2.2. Collimation
        11.2.3. Heel Effect
    11.3. Acquisition Systems
        11.3.1. Screen/Film
        11.3.2. Digital
        11.3.3. Dual-energy
        11.3.4. Linear Tomography
        11.3.5. Tomosynthesis
    11.4. Image Characteristics
        11.4.1. Spatial Resolution
        11.4.2. Contrast Sensitivity
        11.4.3. Noise
        11.4.4. Temporal Resolution
        11.4.5. Artifacts
        11.4.6. Body Part and View-specific Image Processing
        11.4.7. Computer-aided Detection (CAD)
    11.5. Application Requirements
        11.5.1. Chest
        11.5.2. Abdomen
        11.5.3. Spine
        11.5.4. Extremities
        11.5.5. Pediatrics and Neonatal
        11.5.6. Portable/Mobile
    11.6. Dosimetry
        11.6.1. Entrance Skin Exposure
        11.6.2. Effective Dose
        11.6.3. Appropriate Organ Doses
        11.6.4. Doses for Different Procedures
        11.6.5. Technique Optimization
    11.7. Factors Affecting Patient Dose
        11.7.1. Technique (e.g., kVp, mA, time)
        11.7.2. Imaging Geometry

11.7.3. Beam Filtration and Grid
11.7.4. Field Size
11.7.5. Exposure Class
11.8. Technical Assessment and Equipment Purchase Recommendations
11.9. Quality Control (QC) Tests and Frequencies
11.10. Guidelines
11.10.1. Reference Levels

Example Q&A:

Q1. Which factor in a radiographic imaging system is responsible for the heart appearing enlarged on an AP chest image as compared to a PA chest?



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
E. increased parallax from x-ray tubes with both large and small focal spots

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 focus-to-image detector distance and the 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.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012. p. 207–208.

Q2. Portable x-ray images are generally inferior to those taken on stationary radiographic units. One of the reasons is that high-ratio grids are generally not used when acquiring portable radiographs, whereas they are used with stationary x-ray units. 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. Grids in general are not used in portable x-ray radiography as they increase exposure times.
E. One cannot manufacture high-ratio grids 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.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 233–234.

Q3. Which quantity is used to assess radiation risks to an individual organ that also incorporates the type of radiation involved?

A. absorbed dose (mGy)
B. equivalent dose (mSv)
C. effective dose (mSv)
D. kerma (mGy)
E. exposure (C/kg)

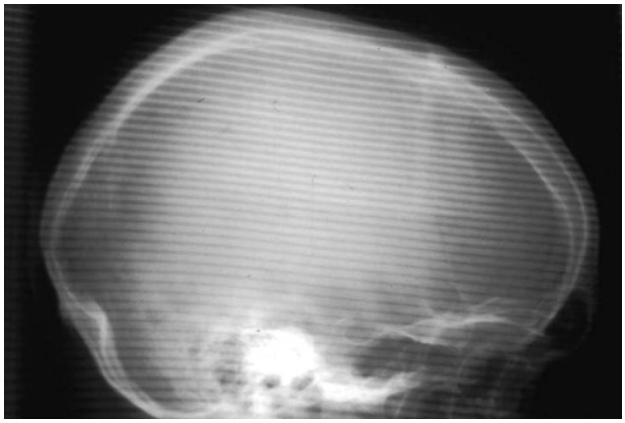
Answer: B – equivalent dose (mSv)

Explanation: Equivalent dose is the absorbed dose multiplied by a radiation weighting factor w_R, where w_R is the relative biological damage caused by radiation of type R. For example, $w_R = 1$ for x-rays, gamma rays, and electrons, and $w_R = 20$ for alpha particles. Absorbed dose is simply a "mechanical" quantity—energy absorbed per unit mass. Effective dose is a weighted sum of organ/tissue equivalent doses where the weighting factors, w_T, are the relative organ/tissue sensitivities for stochastic effects. Kerma, another mechanical quantity, is the kinetic energy released (but not necessarily all absorbed) in matter per unit mass. For x-rays, it is the initial kinetic energy of the ejected electrons per unit mass. Exposure is defined only in air and is the amount of ionized charge (of one sign) per unit mass.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 52–59.

Q4. Identify the artifact in the image below.



A. a corrupted point in k-space
B. grid lines
C. interference pattern between grid lines and detector pixels
D. grid inserted upside down
E. patient motion

Answer: D – grid inserted upside down

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.

Reference:

1. Image from Barry Burns, University of North Carolina. Posted on the Upstate Medical University, State University of New York website at http://www.upstate.edu/radiology/education/rsna/radiography/artifact/ .

Q5. In comparing screen-film to digital radiographic systems, which of the following statements is true?

A. Films can be overexposed, whereas digital systems are immune to overexposures.
B. Digital images always have higher signal-to-noise ratios (SNRs) than film images.
C. Film images generally have higher spatial resolution than digital images.
D. Digital image brightness and contrast can be adjusted by window and leveling. The same can be done with film by using a variable brightness view box.
E. Digitizing a radiographic film is equivalent to acquiring a digital image.

Answer: C – Film images generally have higher spatial resolution than digital images.

Explanation: A. Pixels can be saturated at high enough exposures so that image contrast can be seriously compromised or lost. B. At very low exposures, digital SNRs can be lower than film due to electronic noise becoming proportionally more significant. C. Film screen systems are not pixelated, and high-resolution films with thin screens have superior spatial resolution than digital systems. D. Once a film is processed, its contrast (slope of the H&D curve) is fixed; no variations in back lighting can

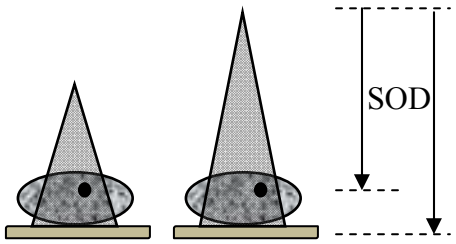
change this. E. Digital imaging captures the full range of exposures to the image receptor (CR or DR), whereas film is limited by reduced contrast in the "toe" and "shoulder" regions of its H&D curve. Information lost in these regions cannot be regained.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 226–227.

Q6. Under automatic exposure control (AEC), increasing the SID from 40" to 72" in radiography results in

A. increased focal spot blurring
B. decreased focal spot blurring
C. an increase in patient exposure
D. noisier images
E. shorter exposure times



Answer: B – decreased focal spot blurring

Explanation: A & B. Focal spot blur decreases with decreasing geometric magnification (M = SID/SOD, see question 1). 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. C. 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. D. Using AEC, the dose to the image receptor is constant, irrespective of the SID, so image quantum noise remains the same. E. Since the image receptor is further away, longer exposure times are needed to keep the image receptor dose constant (assuming the kVp and mA are fixed).

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012 p. 207–208.

Q7. List the following in terms of increasing effective dose:

1. abdomen
2. extremities
3. two view mammogram (both breasts)
4. posteroanterior chest
5. shoulder

A. 2, 1, 5, 4, 3
B. 5, 1, 3, 4, 2
C. 3, 4, 1, 2, 5
D. 4, 3, 1, 2, 5
B 2, 5, 4, 3, 1

Answer: E – 2, 5, 4, 3, 1

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.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 956.

Q8. A patient is five weeks pregnant and was referred for an x-ray examination of the pelvis. As the attending physician on duty, the technologist comes to you asking what she should do. What is the *first* step you should take before considering to proceed?

A. immediately cancel the exam unconditionally
B. re-confirm the pregnancy with a second pregnancy test
C. discuss the risks and benefits of the exam with the patient
D. discuss with the referring physician whether the exam is medically justified at this time
E. instruct the technologist to use a very low-dose technique

Answer: D – discuss with the referring physician whether the exam is medically justified at this time

Explanation: The first step is to ensure the exam is truly necessary through discussion with the referring physician. This means whether a non-ionizing modality (MRI, US) could be used instead, or whether the scan could be deferred until after pregnancy or later during the gestation period. Only proceed if the exam is deemed medically necessary and there are no satisfactory alternatives.

Reference:

1. 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, p. 108.

Q9. What is the single most important component of a radiographic system for determining patient radiation dose?

A. focal spot size
B. x-ray generator power rating
C. x-ray generator type (3 phase, high frequency, falling load)
D. parameter settings of the automatic exposure control (AEC)
E. tabletop attenuation

Answer: D – parameter settings of the automatic exposure control (AEC)

Explanation: The AEC system sets the total exposure to the image receptor for each image. When this exposure limit is reached the x-rays are terminated. The exposure level sets the signal-to-noise ratio (SNR) for digital images or the average optical density for screen-film systems. It also controls how the kV and mA change for patients of different thicknesses. Thus, patient doses can change by up to factors of approximately three or four, depending upon the AEC settings.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 223–224.

Q10. For a KUB on an average-sized patient, what would be a reasonable technique, taking into account the tradeoffs among patient dose, image contrast, image noise, and minimization of patient motion?

A. 75 kVp, 400 mA, 50 ms
B. 120 kVp, 800 mA, 15 ms
C. 50 kVp, 100 mA, 500 ms
D. 75 kVp, 100 mA, 25 ms
E. none of the above

Answer: A – 75 kVp, 400 mA, 50 ms

Explanation: We know that patient dose decreases with increasing kVp, but so does subject contrast. Lower kVps and lower tube currents (mA) require longer imaging times, thus increasing the potential for patient motion. Very low mA values lead to noisy images. Knowing this, we can eliminate answer B because 120 kVp gives too low contrast (although the dose would be low and imaging time short). We can eliminate answer C because of the lengthy imaging time and the higher dose from the more weakly penetrating 50 kVp beam (but contrast would be high). Answer D can be eliminated because 100 mA is inordinately low for a KUB, and with an exposure time of 25 ms would result in an unacceptably noisy image at 2.5 mA. Answer A is a reasonable compromise at 20 mA, with a reasonable short imaging time and a moderate kVp.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 223.

Q11. Assume radiographs are being acquired using automatic exposure control (AEC) at the level of the kidneys. In taking radiographs of a pregnant patient, what is the single most important thing that you could do to ensure the lowest dose to the fetus while maintaining, or even improving, image quality?

A. Use a high kVp since this will result in a lower mAs and decreased dose using AEC.
B. Wrap the patient's abdomen in a lead apron to cover the fetus.
C. Collimate the x-ray field to cover the smallest area of anatomy required to be imaged.
D. Have the patient lie prone, as opposed to supine, on the examination table.
E. Remove the anti-scatter grid.

Answer: C – Collimate the x-ray field to cover the smallest area of anatomy required to be imaged.

Explanation: A. High kVps lead to lower doses, but to decreased image contrast as well. B. 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. C. 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. D. Prone or supine makes little difference with regard to internal scatter to the fetus. E. 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.

Reference:

1. 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, p. 226.

Module 12: Mammography

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Describe unique features of mammography tubes and how they affect the x-ray spectrum produced.
2. Describe automatic exposure control (AEC) performance. Explain compression benefits.
3. Review magnification techniques.
4. Describe the characteristics of the different detectors used in mammography, e.g., screen-film and full-field digital mammography systems.
5. Discuss breast radiation dosimetry.
6. Discuss the Mammography Quality Standards Act (MQSA) and its effect on mammography image quality and dose.

Clinical Application:

1. Describe appropriate uses of the different targets and filters available in mammography systems.
2. Explain when magnification is indicated.
3. Associate image quality changes with radiation dose changes.
4. What are the MQSA training and CME requirements for radiologists, technologists, and physicists?
5. What are the QA requirements of MQSA for digital mammography?

Clinical Problem-solving:

1. Identify factors influencing image contrast and detail as they relate to the visualization of lesions in mammography.
2. Discuss possible image artifacts in mammography and corrective methods that could be used to reduce them.

Concise Syllabus:

12.1. Clinical Importance
12.2. Mammography Equipment
- 12.2.1. Dedicated X-ray Tube
- 12.2.2. Focal Spot
- 12.2.3. Target-Filter Combinations
- 12.2.4. X-ray Spectra
- 12.2.5. Low Peak Kilovoltage (kVp)
- 12.2.6. Half-value Layer (HVL)
- 12.2.7. Breast Compression Paddle
- 12.2.8. Collimation
- 12.2.9. Grids
- 12.2.10. Automatic Exposure Control

12.3. Geometry
- 12.3.1. Source-to-image Receptor Distance (SID)
- 12.3.2. Source-to-object Distance (SOD)
- 12.3.3. Object-to-image Receptor Distance (OID)
- 12.3.4. Heel Effect

12.3.5. Magnification
12.3.6. Advantages of Magnification
12.4. Acquisition Systems
12.4.1. Screen/Film
12.4.2. Full-field Digital Mammography
12.4.3. Stereotactic Biopsy Systems
12.5. Artifacts
12.6. Radiation Dose
12.6.1. Entrance Skin Exposure
12.6.2. Average Glandular Dose
12.6.3. Dose Limits
12.6.4. Factors Affecting Radiation Dose
12.6.5. Radiation Risk vs. Benefits of Screening
12.7. Viewing Images
12.7.1. Dedicated Viewboxes and Displays
12.7.2. Lighting Requirements: Luminance and Illuminance
12.7.3. Dedicated PACS
12.8. Quality Control
12.8.1. Mammography Quality Standards Act (MQSA)
12.8.2. Radiologist, Physicist, Technologist Requirements
12.8.3. American College of Radiology (ACR) Accreditation

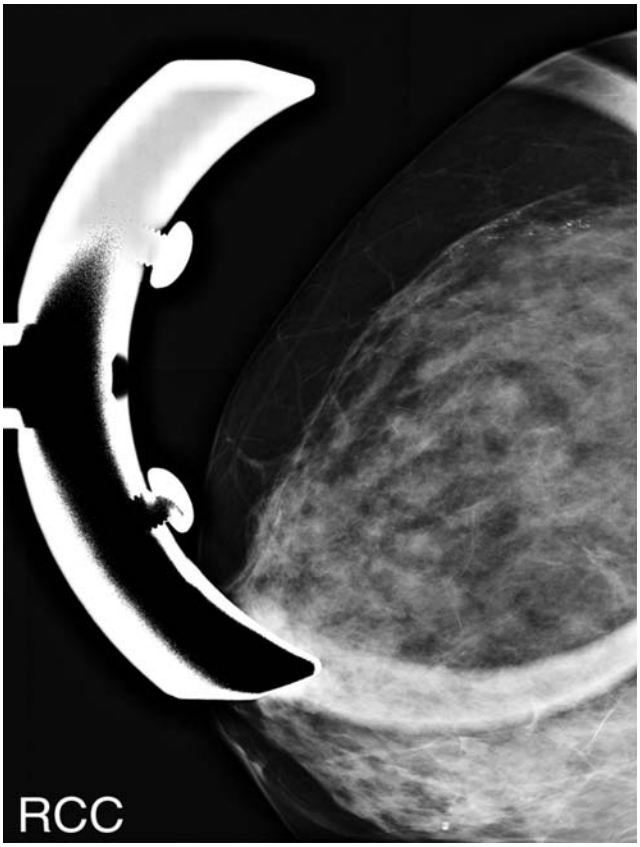
Detailed Curriculum:

12. Mammography
12.1. Clinical Importance
12.1.1. Benefits and Risks
12.1.2. Purpose of Screening Mammography
12.1.3. Diagnosis and Detection Requirements
12.1.4. Attenuation Characteristics of Breast Tissue and Lesions
12.2. Spectrum Requirements
12.2.1. Anode Material
12.2.2. kVp
12.2.3. Filtration
12.2.4. HVL
12.3. Geometrical Requirements
12.3.1. Source-to-image Receptor Distance (SID), Source-to-object Distance (SOD), and Object-to-image Receptor Distance (OID)
12.3.2. Focal Spot Size
12.3.3. Collimation
12.3.4. Beam Central Axis
12.3.5. Chest-Wall Coverage
12.3.6. Heel Effect
12.3.7. Grid vs. Air Gap
12.3.8. Magnification
12.4. Acquisition Systems
12.4.1. Screen/Film
12.4.2. Full-field Digital Mammography
12.4.3. Stereotactic Biopsy Systems

12.4.4. Tomosynthesis
12.5. Compression
12.6. Dose
12.6.1. Entrance Skin Exposure
12.6.2. Average Glandular Dose
12.6.3. AEC
12.6.4. Technique Optimization
12.7. Factors Affecting Patient Dose
12.7.1. Breast Composition
12.7.2. Breast Thickness and Compression
12.7.3. Dose Limits
12.7.4. Techniques
12.7.5. Screening Exams
12.7.6. Diagnostic Examinations, Including Magnification
12.8. Digital Image Processing
12.8.1. Skin Equalization
12.8.2. Advanced Proprietary Processing
12.8.3. Computer-aided Detection (CAD)
12.9. Artifacts
12.9.1. Film and Processing
12.9.2. Digital
12.10. MQSA Regulations
12.10.1. Responsibilities of Physician, Technologist, and Physicist
12.10.2. Dose Limits
12.10.3. Image Quality and Accreditation Phantom
12.10.4. QC Tests and Frequencies
12.11. American College of Radiology (ACR) Accreditation
12.12. Technical Assessment and Equipment Purchase Recommendations

Example Q&A:

Q1. What kind of artifact is seen in the following mammogram?



A. positioning
B. motion
C. contrast
D. noise

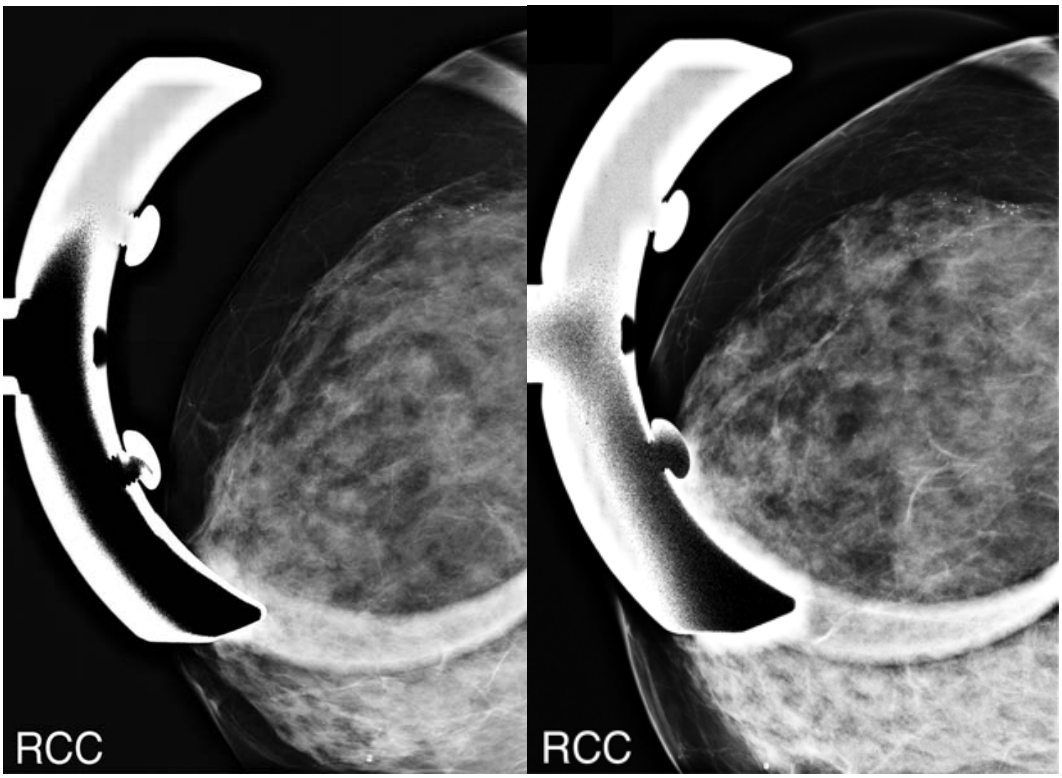
Answer: B – motion artifact

Explanation: As at screen-film mammography, longer exposure times can lead to detection of patient motion at digital mammography. To verify that an artifact is caused by motion, the technologist should review the exposure parameters and technical factors to rule out other causes such as poor technique or long exposure.

Reference:

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

Q2. The left mammogram image shows motion artifact, and the right mammogram shows the corrected image. What was the change in acquisition parameter that resulted in a corrected image?



A. decreased compression
B. increased kVp
C. increased exposure time
D. increased mAs

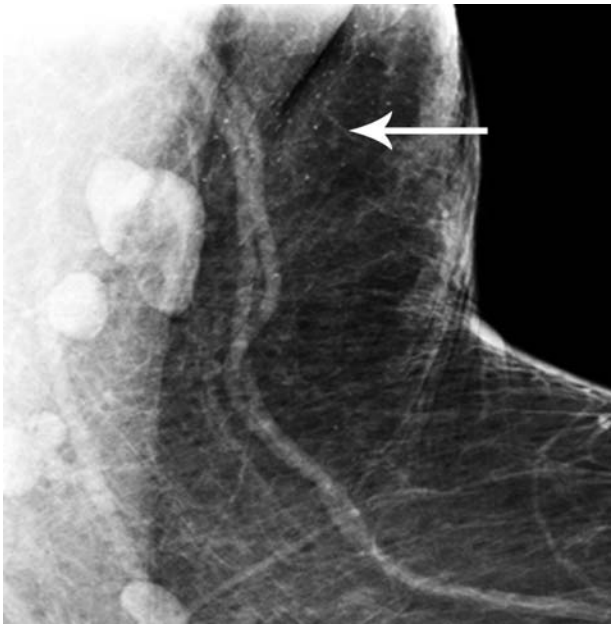
Answer: B – increased kVp.

Explanation: To avoid this kind of artifact and ensure optimal image quality, it is important to instruct the patient to remain still during imaging. Other ways to decrease motion include increasing compression, increasing the kilovolt peak, or using a rhodium target rather than a molybdenum target. However, the latter two solutions can result in lower image contrast, although this may not be clinically significant at digital mammography due to its higher image contrast compared with screen-film mammography.

Reference:

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

Q3. What is your finding in the breast axillary region?



A. skin fold artifact
B. motion artifact
C. antiperspirant artifact
D. noise

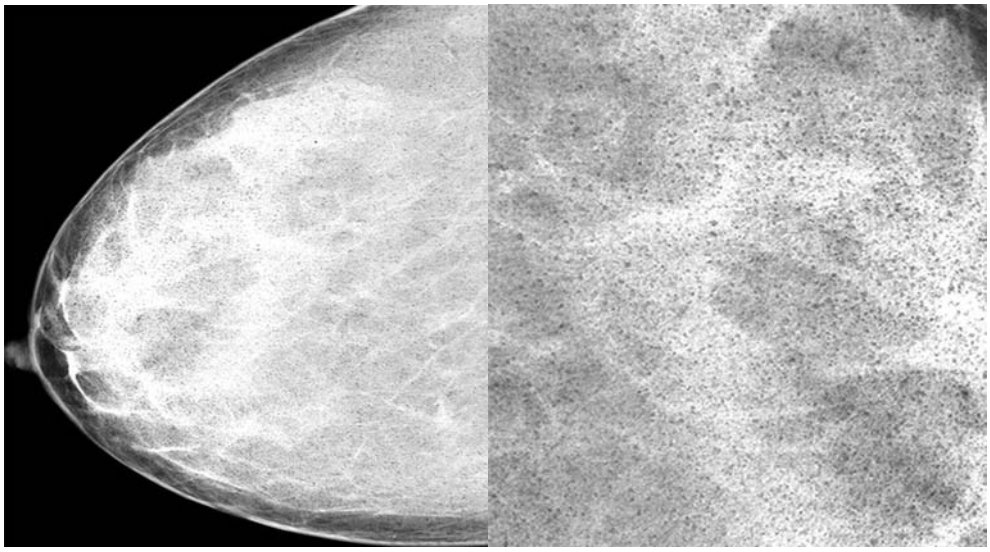
Answer: C – antiperspirant artifact

Explanation: Prior to undergoing mammography, whether screen-film or digital, 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:

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

Q4. The salt and pepper artifact effect caused in the images below is due to _____?



A. over exposure
B. under exposure
C. motion
D. low contrast

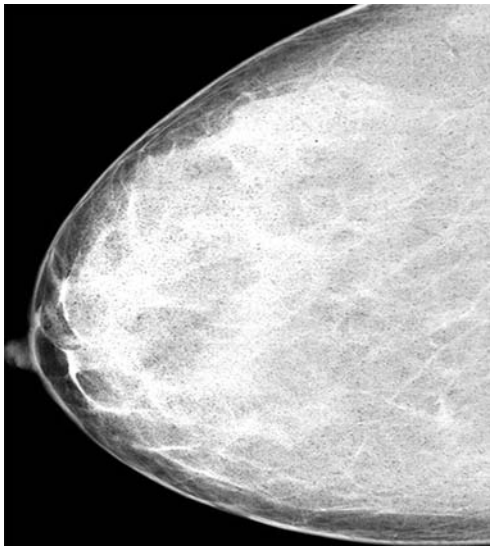
Answer: B – under exposure

Explanation: RCC mammogram obtained at 28 kVp 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:

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

Q5. In mammographic image acquisition, it is important to use an appropriate exposure time to ensure that the signal-to-noise ratio is higher so that signal and noise can easily be differentiated. In the following underexposed image the artifact is due to_____.



A. high kVp used
B. placement of photo cell
C. motion
D. low contrast

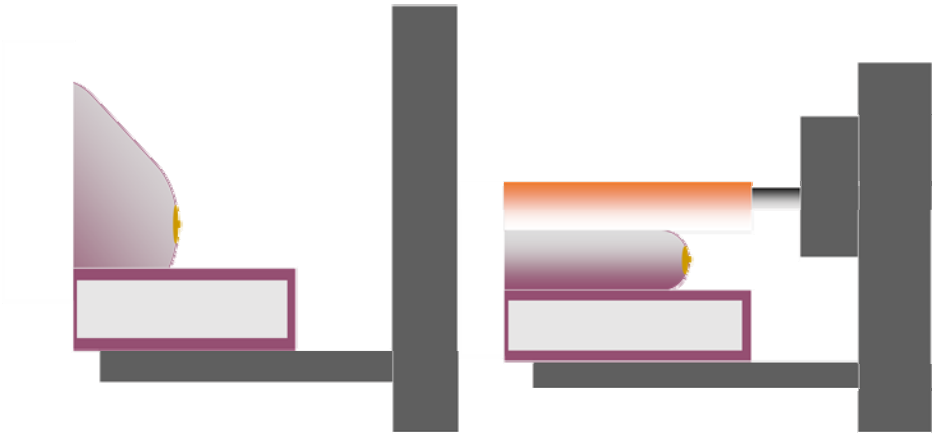
Answer: B – placement of photo cell

Explanation: The photocell has accidentally been positioned close to the edge of the breast. In this case, because the edge of the breast is an area of thin tissue, the x-ray unit may have mistakenly interpreted it as a thin breast and therefore used a shorter exposure time, which is typically used for imaging thin breasts.

Reference:

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

Q6. In mammography, compression _____



A. decreases x-ray scatter, increases geometric blurring
B. increases x-ray scatter, increases geometric blurring
C. decreases x-ray scatter, decreases geometric blurring
D. comforts the patient

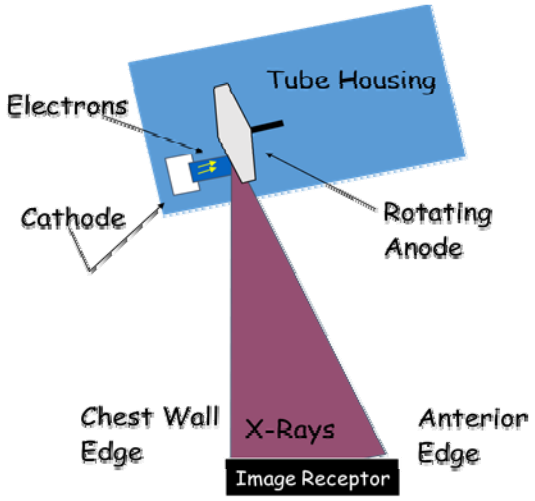
Answer: C – decreases x-ray scatter, decreases geometric blurring

Explanation: Breast compression reduces overlapping anatomy and decreases tissue thickness of the breast. This results in less scatter, more contrast, less geometric blurring of the anatomic structures, less motion and lower radiation dose to the tissues.

Reference:

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

Q7. During mammography acquisition, the cathode-anode axis is placed from the chest wall to nipple as shown. This helps to _____



A. achieve a more uniform exposure
B. maximize heel effect at chest wall
C. minimize motion
D. complete the process quickly

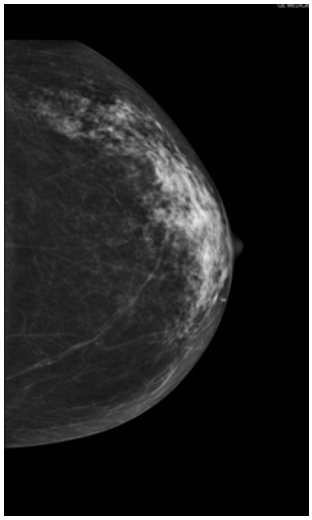
Answer: A – achieve more uniform exposure

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. Also, a more uniform exposure is achieved.

Reference:

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

Q8. What is wrong with the following mammogram?



A. missing tissue
B. placement of photo cell
C. motion
D. low contrast

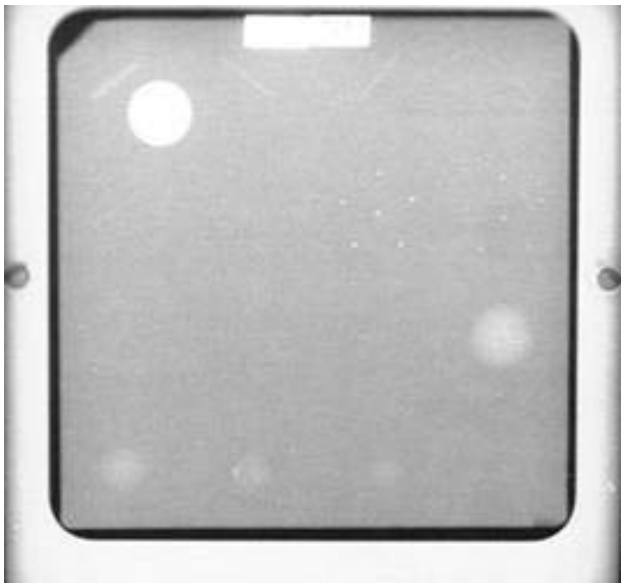
Answer: A – missing tissue

Explanation: This LCC view is cut on the superior portion. This means missing information, and the view needs to be corrected by repeating the view. Repeating the view will result in additional radiation dose to the breast.

Reference:

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

Q9. The following image is an image of a mammography phantom. A typical ACR-approved mammography phantom contains _____.



A. 5 fibers, 5 speck groups, 5 masses
B. 6 fibers, 5 speck groups, 5 masses
C. 4 fibers, 5 speck groups, 5 masses
D. 5 fibers, 4 speck groups, 4 masses

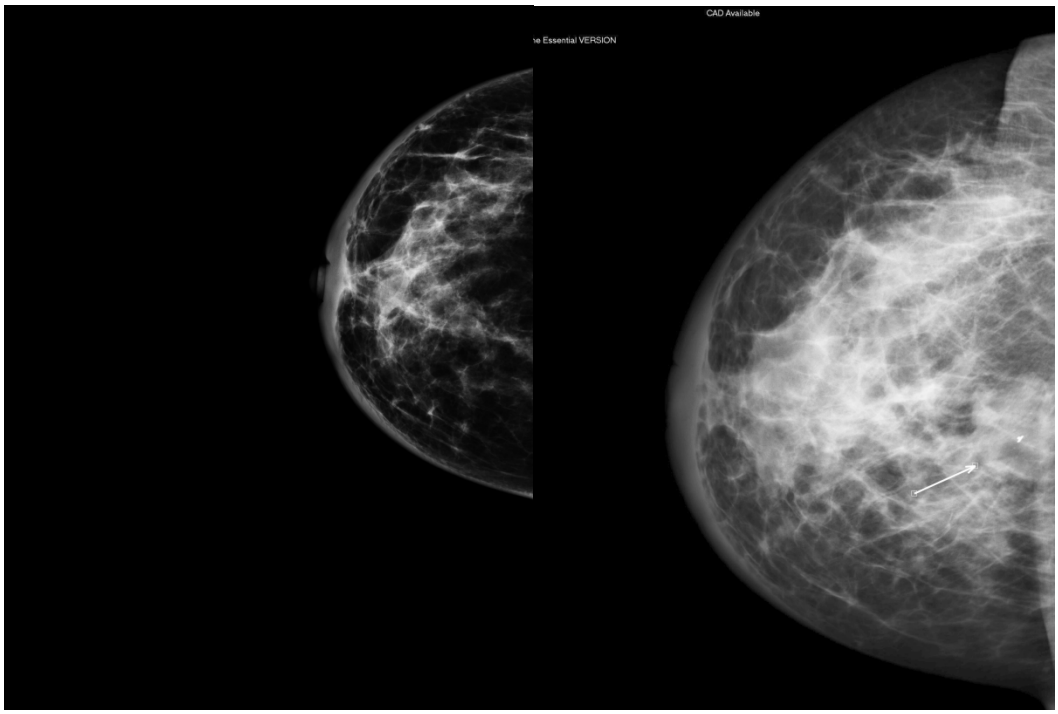
Answer: B – 6 fibers, 5 speck groups, 5 masses

Explanation: Mammography phantoms are used to assess mammographic image quality and to detect temporal changes in image quality. Phantom images should be read under optimal viewing conditions and scored. The phantom image shall achieve at least the minimum score established by the accredited body and accepted by FDA.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.
2. American College of Radiology. *Mammography Quality Control Manual*. Reston, VA: American College of Radiology, 1999.

Q10. In the CC view mammograms below, both of which were done on the same patient on the same day, there is more probability of missing the cancer on the left image because of _____.



A. low contrast
B. not enough tissue included near the chest wall
C. high contrast
D. wrong view

Answer: B – not enough tissue included near the chest wall

Explanation: Positioning plays a key role in mammograms. It is important to include the chest wall (pectoral muscle) correctly while positioning, or else it results in missing information and the view needs to be corrected by repeating the view. Repeating the view will result in additional radiation dose to the breast.

Reference:

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

Module 13: Fluoroscopy and Interventional Imaging

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Describe and identify the basic components of a fluoroscopic system.
2. Explain how the geometric features of a fluoroscopic system contribute to the resulting image.
3. Explain the features and functions of image intensifier (II) systems used for fluoroscopy.
4. Explain the features and functions of flat-panel detector systems used for fluoroscopy.
5. Describe the different operating modes used in fluoroscopy imaging.
6. Identify the components that determine image quality in a fluoroscopy system and the causes of image degradation.
7. Discuss basic image processing methods used in fluoroscopy, and describe how they are used clinically.
8. Review the various application requirements for fluoroscopy and interventional radiology systems.
9. Name the factors that affect patient dose during a fluoroscopic or interventional procedure.
10. Describe concepts of exposure and how patient radiation dose is estimated in fluoroscopy and interventional procedures.
11. Describe the artifacts that can occur with image-intensified and flat-panel fluoroscopy systems.

Clinical Application:

1. Differentiate among the various image acquisition parameters used in specific clinical applications of fluoroscopy and interventional radiology.
2. Describe where the operator should stand to minimize personnel dose when performing an interventional fluoroscopy procedure with the C-arm positioned horizontally?
3. Discuss radiation safety considerations and methods to modify a procedure to minimize the dose for operators of short stature.
4. Describe the geometric and clinical equipment settings which can be implemented to minimize patient peak skin dose in fluoroscopy and interventional radiology.

Clinical Problem-solving:

1. Identify the technique factors and appropriate system features to use to optimize image quality while minimizing patient dose in fluoroscopy and interventional radiology.
2. Describe the geometric factors that affect operator dose during an interventional fluoroscopy procedure.
3. What steps can be taken to minimize the dose to the fetus of a pregnant patient who needs a fluoroscopic or interventional procedure?

Concise Syllabus:

13. Fluoroscopy and Interventional Imaging
    - 13.1. System Components
    - 13.2. Geometry
    - 13.3. Detector Systems
        - 13.3.1. Image Intensifiers
        - 13.3.2. Flat-panel Detectors
    - 13.4. Real-time Imaging Characteristics

13.4.1. Continuous Fluoroscopy
13.4.2. High-Dose Rate Fluoroscopy
13.4.3. Variable Frame-rate Pulsed Fluoroscopy
13.4.4. Spot Images and Fluorography (Serial Imaging)
13.5. Image Quality
13.5.1. Temporal Resolution
13.5.2. Noise
13.5.3. Contrast: kVp and Scatter
13.5.4. Field of View (FOV), Magnification, and Resolution
13.6. Image Processing
13.6.1. DSA
13.6.2. Last-image Hold
13.6.3. Frame Averaging
13.7. Applications
13.8. Dose and Dosimetry
13.9. Technique Optimization and Factors Affecting Patient Dose

Detailed Curriculum:

13. Fluoroscopy and Interventional Imaging
13.1. System Components
13.1.1. Tube
13.1.2. Filtration
13.1.3. Collimation
13.1.4. Grids
13.1.5. Automatic Brightness Control (ABC)
13.1.6. Automatic Brightness Stabilization (ABS)
13.1.7. Compensation Filters
13.2. Geometry
13.2.1. Source-to-image Receptor Distance (SID), Source-to-object Distance (SOD), and Object-to-image Receptor Distance (OID)
13.2.2. Focal Spot Size
13.2.3. Magnification
13.2.4. Under-table vs. Over-table X-ray Tube
13.2.5. C-arms
13.3. Image Intensifier (II) Acquisition Systems
13.3.1. II Structure
13.3.2. Minification Gain
13.3.3. Brightness Gain
13.3.4. Field of View (FOV), Magnification, and Resolution
13.3.5. Camera and Video System
13.3.6. Image Distortions
13.3.6.1. Lag
13.3.6.2. Veiling Glare
13.3.6.3. Vignetting
13.3.6.4. Pincushion, Barreling, “S”-distortion
13.4. Flat-panel Acquisition Systems
13.4.1. Detectors
13.4.2. Magnification

13.4.3. Binning
13.4.4. Comparison to II
13.4.5. Image Distortions
13.4.5.1. Correlated Noise
13.4.5.2. Lag
13.4.5.3. Ghosting
13.5. Real-time Imaging
13.5.1. Continuous Fluoroscopy
13.5.2. High-Dose Rate Fluoroscopy
13.5.3. Variable Frame-rate Pulsed Fluoroscopy
13.5.4. Spot Images
13.5.5. Operation Mode Variations
13.5.5.1. Effective mA
13.5.5.2. Variable Beam Filtration
13.5.5.3. Software Processing
13.6. Image Quality
13.6.1. Low-contrast Sensitivity
13.6.2. High-contrast (Spatial) Resolution
13.6.3. Temporal Resolution
13.6.4. Noise
13.7. Image Processing
13.7.1. Frame Averaging
13.7.2. Temporal Recursive Filtering
13.7.3. Last-image Hold and Last-series Hold
13.7.4. Edge Enhancement and Smoothing
13.7.5. Digital Subtraction Angiography (DSA)
13.7.6. Road Mapping
13.8. Applications
13.8.1. Conventional Fluoroscopy (e.g., GI, GU)
13.8.2. Contrast Imaging (e.g., Iodine, Barium)
13.8.3. Cinefluorography
13.8.4. Interventional
13.8.5. DSA
13.8.6. Bi-plane
13.8.7. Cardiac
13.8.8. Pediatric
13.8.9. Bolus Chasing
13.8.10. Cone-beam CT Imaging
13.9. Dose and Dosimetry
13.9.1. Federal and State Regulations
13.9.1.1. Dose Rate Limits
13.9.1.2. Audible Alarms
13.9.1.3. Recording of “Beam-on” Time
13.9.1.4. Minimum Source-to-Patient Distance
13.9.1.5. Sentinel Event
13.9.2. Dose-Area-Product (DAP) and KERMA-Area-Product (KAP) Meters
13.9.3. Entrance Skin Exposure
13.9.4. Peak Skin Dose

13.9.5. Cumulative Dose
13.9.6. Patient Dose for Various Acquisition Modes
13.9.7. Operator and Staff Dose
13.9.8. Shielding and Protection Considerations

13.10. Technique Optimization and Factors Affecting Patient Dose
13.10.1.1. Technique
13.10.1.2. Filters
13.10.1.3. Acquisition Mode
13.10.1.4. Exposure Time
13.10.1.5. Last-image Hold
13.10.1.6. Pulsed Exposure
13.10.1.7. Magnification
13.10.1.8. Collimation
13.10.1.9. Geometry
13.10.1.10. Operator Training

Example Q&A:

Q1. Which of the following statements about fluoroscopic radiation dose is TRUE?

A. Fluoroscopic exposure time is the easiest metric to quantify and is therefore the best estimate for a patient's fluoroscopic radiation dose.
B. Air Kerma at the reference point ($K_{a,r}$) is equivalent to the patient entrance skin dose if it is corrected for the inverse square effect.
C. Air Kerma Area Product (P_{KA}), also known as the Dose Area Product, may be effectively used for estimating stochastic risk rather than deterministic risk for the exposed patient.
D. Peak Skin Dose (PSD or $D_{skin,max}$) can be easily and accurately calculated in real time and is an effective metric for predicting deterministic skin injuries following fluoroscopic exposure.
E. Prolonged fluoroscopy with cumulative dose exceeding 15 Grays over all exposed fields is considered a sentinel event.

Answer: C – Air Kerma Area Product (P_{KA}), also known as the Dose Area Product, may be effectively used for estimating stochastic risk rather than deterministic risk for the exposed patient.

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). Currently, measurement of peak skin dose cannot be easily and accurately calculated in real time unless special instruments (real-time dosimetry) are used. The Joint Commission defines a fluoroscopic sentinel event as prolonged fluoroscopy with a cumulative dose exceeding 15 Gray to a single field, not over all exposed fields.

Reference:

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.

Q2. Which of the following non-deterministic tissue effects should be considered for a fluoroscopic procedure resulting in high, single-site acute skin doses?

A. erythema (skin reddening)
B. epilation (hair loss)
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. (Reference – NCRP 168. Table 2.5)

Q3. Additional dose-management actions are recommended after thresholds for a substantial radiation dose level (SRDL) are exceeded. Which of the following thresholds should a fluoroscopist pay attention to?

i. peak skin dose exceeding 3 Grays
ii. dose to a single field exceeding 1500 rads (15 Grays)
iii. fluoroscopy Time exceeding 60 minutes
iv. reference Air Kerma exceeding 5 Grays
v. air Kerma Area Product exceeding 500 Gy cm^2

A. Pay attention to threshold ii. only.
B. Pay attention to threshold i. for deterministic effects and v. for stochastic effects only.
C. Exceeding any one of the thresholds should initiate dose management actions.
D. Any three of the five thresholds must be exceeded before dose management actions.
E. All of the five thresholds must be exceeded before initiating dose management actions.

Answer: C – exceeding any of the thresholds should initiate dose management actions.

Reference:

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, Chapter 4.

Q4. It is important for the fluoroscopist to know the operational settings of the system being used. In general, fluorsocopic systems can be operated with automatic exposure control (AEC), but the exposure level or the pulse rate may be selected in order to minimize patient exposures. Arrange the following fluoroscopic settings in terms of DECREASING patient exposure. (pps = pulses per second)

i. Pulsed, High Level, 30 pps
ii. Pulsed, 15 pps
iii. Continuous
iv. Cine

A. i, ii, iii, iv
B. iv, iii, ii, i
C. iii, iv, i, ii
D. iv, iii, i, ii
E. ii, i, iv, iii

Answer: D – iv, iii, i, ii

Explanation: All exposure factors including kVp and mA remaining equal, cine fluoroscopy results in the highest patient radiation exposure and should be used sparingly. Of this list, pulsed fluoroscopy at 15 pulses per second provides the lowest patient radiation exposure. Continuous fluoroscopy delivers higher patient radiation exposures than pulsed fluoroscopy.

Reference:

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

Q5. Which of the following is an example of POOR clinical practice with fluoroscopy?

A. requiring the use of radiation dosimeters and personal protective equipment (e.g., aprons, neck shields, etc.) for all personnel in the fluoroscopic use room.
B. positioning the image receptor as close to the patient surface and the x-ray tube as far from the patient surface as possible.
C. selecting the appropriate magnification mode and using collimation to only irradiate the area or organ of interest.
D. placing a lead apron in the radiation field to reduce exposure in other areas of the patient.
E. enabling system features, such as last image hold (LIH) and pulsed fluoroscopy, if applicable.

Answer: D – placing a lead apron in the radiation field to reduce exposure in other areas of the patient.

Explanation: Placing a lead apron, or any highly attenuating object, in the radiation field can result in a higher radiation technique (higher kVp, or mA, or both) resulting in higher patient dose. This is particularly relevant for systems operating in automatic exposure control modes.

Reference:

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

Q6. Artifacts in fluoroscopy can be highly dependent on the type of image receptor being used. Respectively, image intensifier (II) type image receptors are susceptible to a/an _____ artifact, while flat panel type image receptors are susceptible to a/an _____ artifact.

A. pincushion distortion; dead-pixel drop-off
B. beam hardening; digital reconstruction
C. quantum mottle, brightness gain
D. gray scale saturation; vignetting
E. persistence; s-distortion

Answer: A – pincushion distortion; dead-pixel drop-off

Explanation: Pincushion distortion is specific to image intensifier-based fluoroscopic systems, while dead pixels are specific to flat panel-based fluoroscopic systems, which can result in artifacts. Beam hardening and digital image reconstruction artifacts are more relevant to CT. Brightness gain, vignetting, and S-distortion are more relevant to image intensifier-based fluoroscopic systems than flat panel systems.

Reference:

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

Module 14: CT

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Identify the major components of a CT system.
2. Describe the differences between conventional and helical scanning.
3. Explain the equipment differences between single-slice and multi-slice helical scanning.
4. Explain the difference between reconstructing and reformatting an image.
5. Explain how dose modulation affects patient dose.
6. List the image acquisition parameters, and explain how each affects the CT image quality.
7. Define the Hounsfield unit, and describe how a CT image is formed.
8. Compare image characteristics of CT to other modalities, such as digital radiography.
9. Describe the concepts of CT Dose Index (CTDI), Dose-length Product (DLP), Effective Dose, and Organ Dose.
10. Understand how the reconstruction kernel (i.e., software filter) selected affects image quality.
11. Describe common artifacts and their causes.
12. Describe the relationship between contrast resolution and radiation dose and the effect of imaging parameters on both.
13. Explain over-beaming and over-ranging and how each affects patient dose.
14. Identify the sources of CT image artifacts, and describe how those artifacts may be eliminated or reduced.

Clinical Application:

1. List typical CT numbers for tissues such as air, water, fat, blood, brain, and bone.
2. Explain why pre-set window width and levels are selected for viewing images.
3. Describe the modes of CT operation and their clinical applications.
4. Identify several clinical applications where multi-slice helical scanning is employed.
5. Differentiate among the different rendering techniques used in 3D imaging.
6. Discuss the radiation exposure to patients and personnel during CT fluoroscopy.

Clinical Problem-solving:

1. Specify the image acquisition parameters that affect patient radiation dose, and describe how dose can be minimized.
2. Review the considerations necessary when a CT scan needs to be performed on a pregnant patient.
3. Discuss the use of breast shields and lead shielding in CT.
4. Discuss appropriate protocols for pediatric CT.

Concise Syllabus:

14. CT
    - 14.1. System Components
    - 14.2. System Geometry
    - 14.3. Parameters for Image Acquisition
        - 14.3.1. kVp
        - 14.3.2. mA

14.3.3. Rotation Time
14.3.4. Table Speed
14.3.5. Pitch
14.3.6. Rotational Data Acquisition
14.3.7. Image Slice Thickness vs. Beam Width
14.4. Image Formation
14.4.1. Linear Attenuation Coefficient
14.4.2. Hounsfield Unit Definition
14.4.3. Filtered Back Projection
14.4.4. Helical Reconstruction
14.5. Modes of Operation
14.6. Image Contrast, Detail, and Noise
14.7. Artifacts
14.8. Image Processing and Display
14.9. Clinical Application and Protocols
14.10. Dose and Dosimetry
14.11. Technique Optimization and Factors Affecting Patient Dose

Detailed Curriculum:

14. Computed Tomography (CT)
14.1. System Components
14.1.1. System Geometry
14.1.2. Tube (Fixed and Flying Focal Spot)
14.1.3. Beam Shaping (Bow-tie) Filters
14.1.4. Beam Filtration
14.1.5. Collimation
14.1.6. Data Acquisition System
14.1.7. Detector Types and Arrays
14.2. System Types
14.2.1. Third Generation
14.2.2. Electron Beam
14.2.3. Dual Source
14.2.4. Cone-beam
14.3. Image Acquisition Parameters
14.3.1. kVp
14.3.2. mAs and Effective mAs
14.3.3. Rotation Time
14.3.4. Pitch (Collimator)
14.3.5. Slice Thickness and Sensitivity Profile
14.3.6. Detector Binning
14.4. Image Formation
14.4.1. Back Projection
14.4.2. Filtered Projection
14.4.3. Reconstruction Filters
14.4.4. Helical Reconstruction
14.4.5. Cone-beam Reconstruction
14.4.6. Linear Attenuation Coefficient
14.4.7. Hounsfield Unit Definition

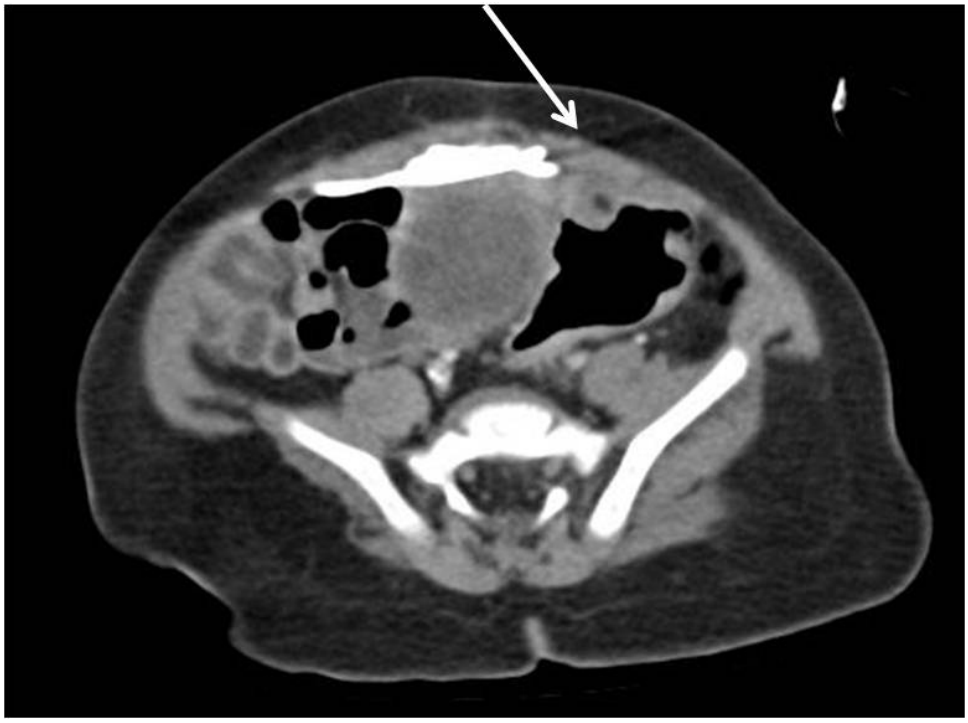
14.4.8. Typical CT Numbers (Hounsfield Units)
14.5. Modes of Operation
14.5.1. Axial and Helical Modes
14.5.2. Fixed mA
14.5.3. Automatic mA
14.5.4. Dose-reduction Techniques
14.5.5. CT Fluoroscopy
14.5.6. Localizer Image (Scout)
14.5.7. Contrast CT
14.5.8. Temporal CT and Perfusion
14.5.9. Dual-energy
14.5.10. CT Angiography
14.6. Image Characteristics and Artifacts
14.6.1. Spatial and Contrast Resolution
14.6.2. Relationships between Acquisition Parameters and SNR
14.6.3. Beam-hardening
14.6.4. Motion
14.6.5. Partial-volume
14.6.6. Incomplete Projections
14.6.7. Photon Starvation
14.6.8. Streak Artifacts
14.6.9. Ring Artifacts
14.6.10. Cone-beam Artifacts
14.7. Image Processing and Display
14.7.1. Pre-set and Variable Display Modes
14.7.2. Multi-planar Reconstruction (MPR)
14.7.3. Maximum Intensity Projection (MIP)
14.7.4. Volume and Surface Rendering
14.7.5. Perfusion
14.8. Clinical Application and Protocols
14.8.1. Head
14.8.2. Spine
14.8.3. Thoracic
14.8.4. Angiography
14.8.5. Cardiac
14.8.6. Abdomen
14.8.7. Virtual Colonoscopy
14.8.8. CT Fluoroscopy
14.8.9. Whole-body
14.8.10. Pediatric
14.8.11. Cone-beam Angiography
14.9. Dose and Dosimetry
14.9.1. Dose Profile
14.9.2. CT Dose Index and CTDIvol
14.9.3. Multiple Scan Average Dose (MSAD)
14.9.4. Dose-Length Product (DLP)
14.9.5. Organ Dose and Effective Dose
14.9.6. Adult and Pediatric Technique Optimization

14.10. Factors Affecting Patient Dose
- 14.10.1. Beam Width and Pitch
- 14.10.2. kVp, mA, and Time
- 14.10.3. Patient Size
- 14.10.4. Slice Increment
- 14.10.5. Scan Length
- 14.10.6. Number of Phases (e.g., Pre- and Post-contrast)
- 14.10.7. Technique Selection
- 14.10.8. Dose Modulation
- 14.10.9. Dual Source
- 14.10.10. Patient Shielding

14.11. Technical Assessment and Equipment Purchase Recommendations

Example Q&A:

Q1. What is the artifact identified by the arrow in the body CT image shown below?



A. patient motion
B. aliasing
C. beam hardening
D. detector failure

Answer: C – beam hardening

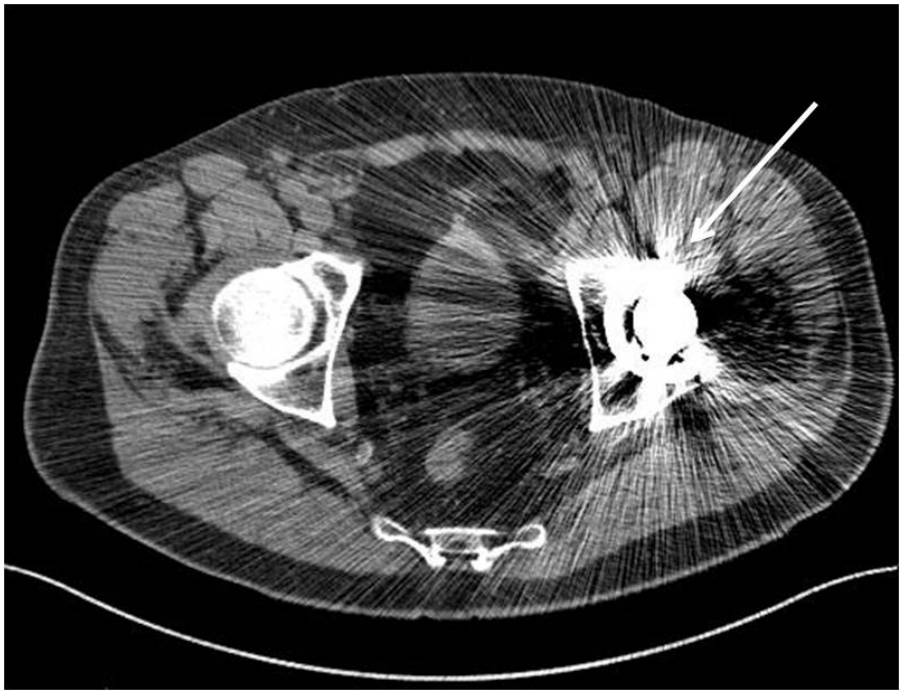
Explanation: Beam hardening is an increase in the average x-ray beam energy as it passes through the patient. Low-energy x-rays are preferentially absorbed in the patient, resulting in a higher energy beam exiting the patient compared to the entrance beam. The density, atomic number, and thickness of

absorbers within a given slice volume will also affect the magnitude of beam hardening that occurs. As each of these factors increases, beam hardening increases. Dark bands are often seen in an image adjacent to high-Z, dense, thick structures. In the image above, a dark streak is seen on both sides of the long axis of the contrast-filled structure indicating the x-ray beam that passed through the contrast agent was more energetic (and therefore attenuated less) than the beam passing through the structure at other angles.

References:

1. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009, p. 208–210.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 369–371.

Q2. Which of the following actions would you take to minimize or eliminate the artifact identified by the arrow in the pelvic CT shown in the figure below?



A. perform an air calibration
B. increase pitch
C. increase beam collimation
D. increase kVp

Answer: D – increase kVp

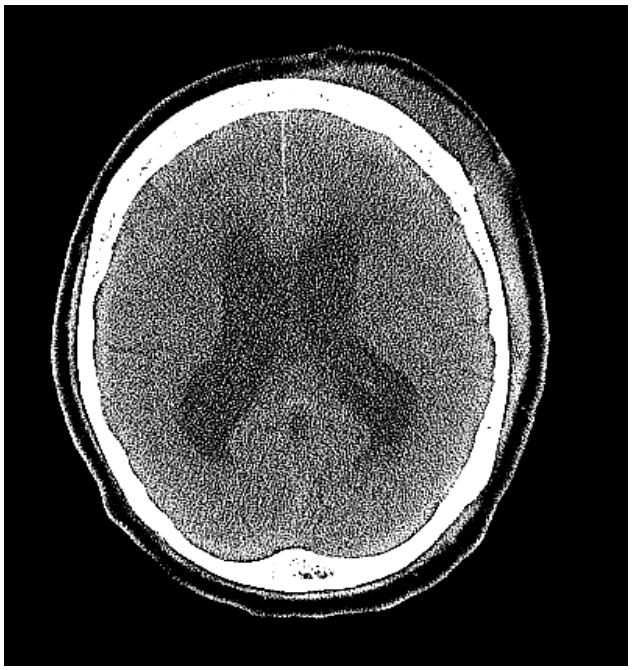
Explanation: The image displays streaking artifact due to the presence of metal within the patient anatomy being imaged. Increasing the kVp will result in higher x-ray beam energy and increase penetration of the beam through the metal, which will reduce streaking. Increasing collimation will result in 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. Changing the pitch may also affect patient dose.

References:

1. Lee, M.J., S. Kim, S.A. Lee, H.T. Song, Y.M. Huh, D.H. Kim, S.H. Han, 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, p. 120.

Q3. Use of which of the following reconstruction options would improve visibility of low-contrast structures in the figure below?



A. lung filter
B. bone filter
C. soft tissue filter
D. thinner reconstructed slice width.

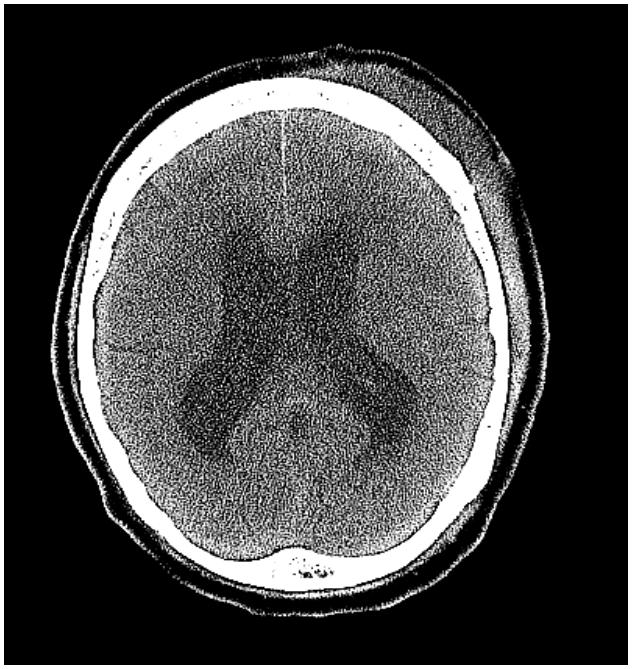
Answer: C – soft tissue filter

Explanation: Noise degrades visibility of low-contrast structures. In order to improve low-contrast visibility, a soft tissue filter would be employed. Soft tissue filters are essentially low-pass filters used to smooth out noise in the image. This improves low-contrast visibility but degrades spatial resolution. The bone and lung filters employed by some CT manufacturers are high-pass filters that are used for edge enhancement or sharpening, however their use results in increased image noise and reduced low-contrast visibility. Thinner reconstructed slice widths result in less signal per image voxel, which also increases noise and reduces low-contrast visibility.

References:

1. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009, p. 73–74, 417.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 355, 369.

Q4. Which of the following would improve visibility of low-contrast structures in the image below without increasing radiation dose to the patient?



A. increase mA
B. increase tube rotation time
C. increase reconstructed slice width
D. increase kVp

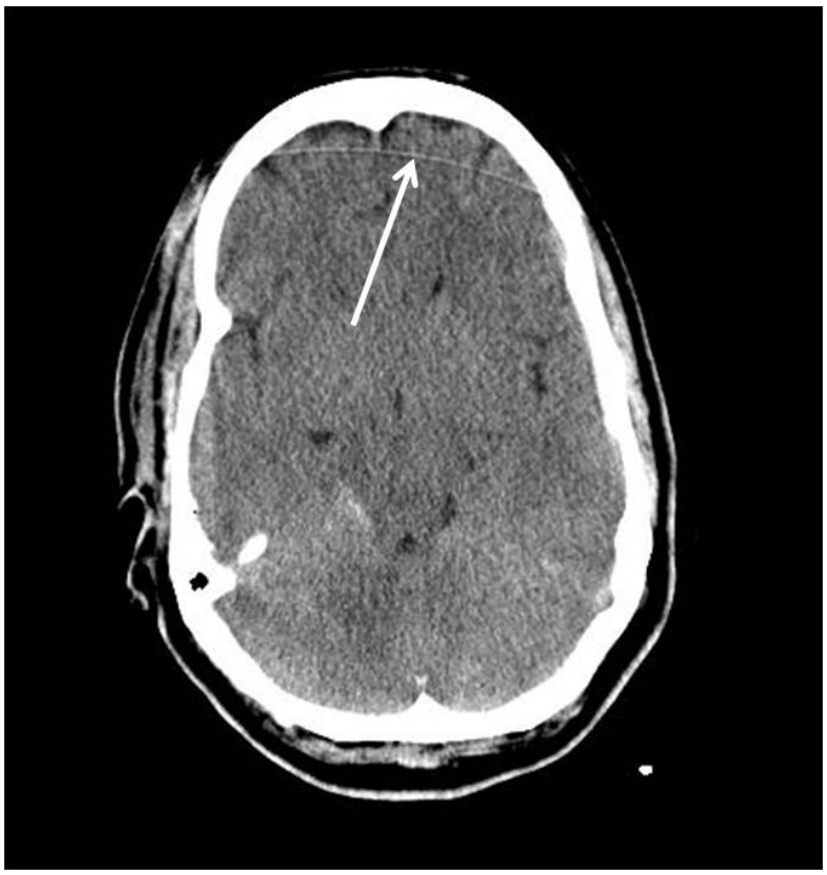
Answer: C – increase reconstructed slice width

Explanation: All of the options listed above will improve visibility of low-contrast resolution. The product of mA and tube rotation time equals the scan mAs. As mAs increases, patient dose increases proportionally. Therefore, an increase in either factor will result in a proportional increase in patient dose. Radiation dose is proportional to the square of the kVp. Increasing kVp from 120 to 140 will result in almost a 40% increase in dose. Increasing the reconstructed slice width will result in more signal per voxel, which will reduce noise and improve low-contrast visibility. The disadvantage of a larger reconstructed slice width is reduced spatial resolution. Often, when thinner slice thickness is desired, dose is increased to compensate for higher noise with thinner slices. In this case, slice thickness is increased, which will reduce noise, so dose would not be expected to increase.

References:

1. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009, p. 230–231.
2. Kofler, J.M. "Scan Acquisition Settings – Trade Offs Between Speed, Resolution, and Dose." Presented at AAPM 2011 Summit on CT Dose, Denver, CO, 2011.

Q5. The artifact indicated by the arrow in the image below is the result of:



A. patient motion
B. beam hardening
C. poor detector calibration
D. partial volume averaging

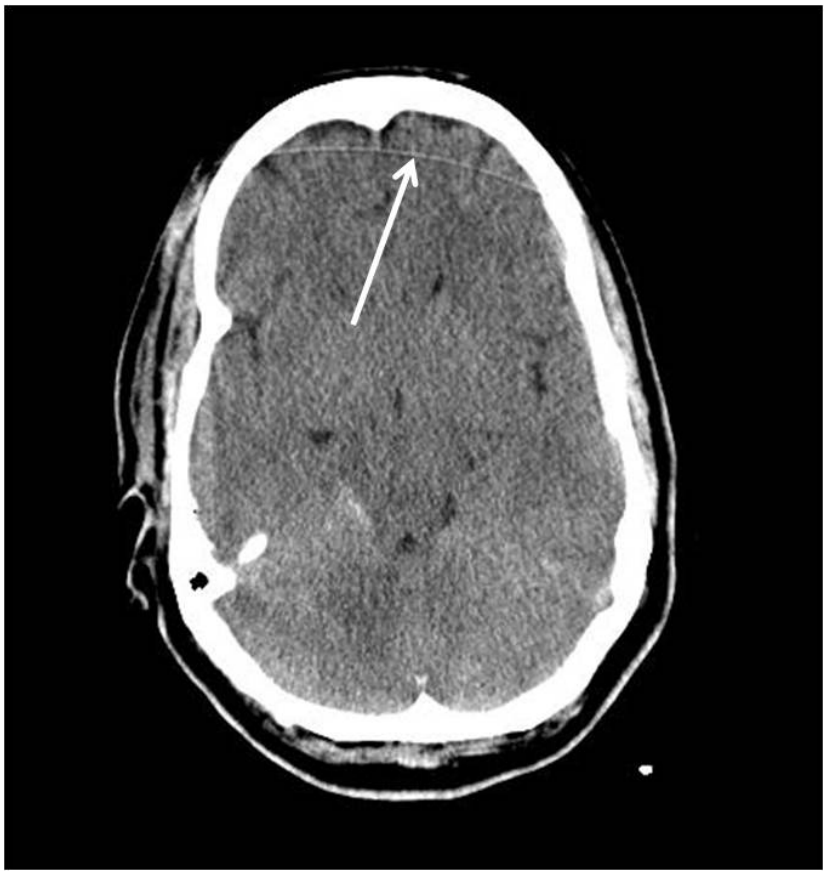
Answer: C – poor detector calibration

Explanation: Note the partial ring artifact in the upper portion of the image. Ring artifacts are the result of poor detector calibration or detector failure.

References:

1. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009, p. 205.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 334–335.

Q6. The artifact indicated by the arrow on the image below may develop in which type of CT scanner?



A. electron beam CT
B. rotate-translate
C. rotate-rotate
D. rotate-stationary

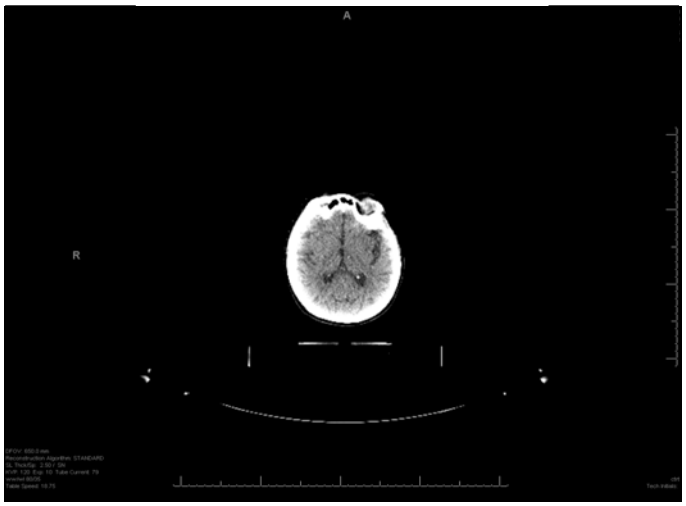
Answer: C – rotate-rotate

Explanation: CT scanner configurations in which the x-ray tube and detector array both rotate around isocenter (rotate-rotate) are subject to ring artifacts. Modern CT scanners utilize rotate-rotate design configurations. Calibration scans are routinely completed to offset any differences in detector gains to help minimize the potential for ring artifacts.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 334–335.
2. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009, p. 205.

Q7. Spatial resolution in the figure below could be improved by:



A. using wider collimation
B. reducing the field of view
C. increasing pitch
D. application of a soft tissue reconstruction filter

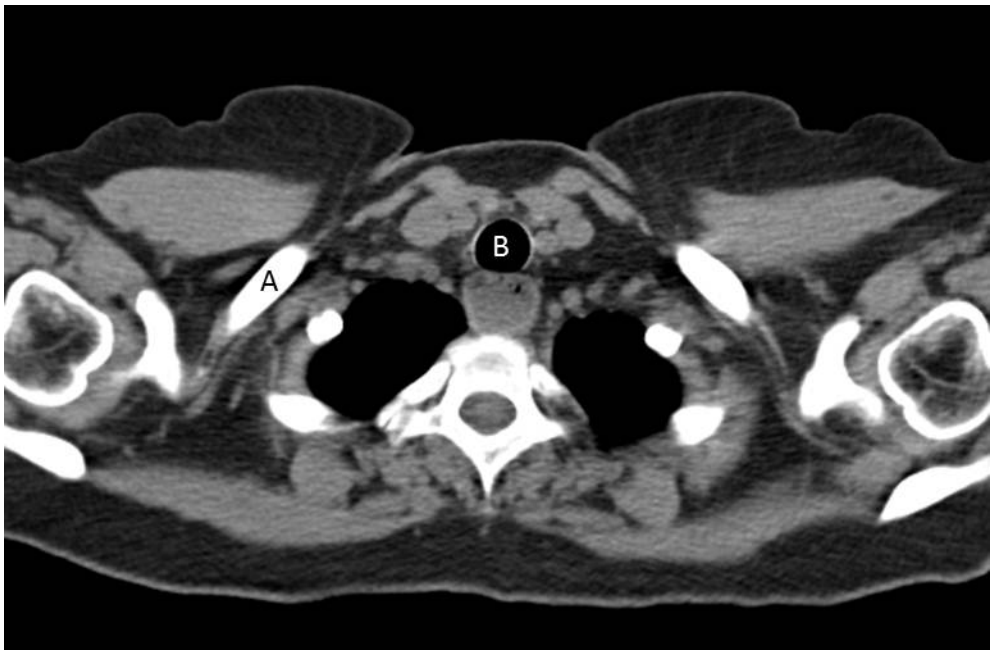
Answer: B – reducing the field of view

Explanation: Wider collimation will result in larger voxel size in the z-direction and reduced spatial resolution. Increasing the pitch will result in an increase in the slice sensitivity profile and reduced spatial resolution. Soft tissue filters employ low-pass filters that smooth out noise and result in more image blur. Reducing the field of view will decrease pixel size, providing better spatial resolution in the image.

References:

1. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009, p. 193.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 369.

Q8. What difference in CT number (HU) is expected between tissue A and tissue B as shown in the figure below?



A. 0
B. 500
C. 1000
D. 2000

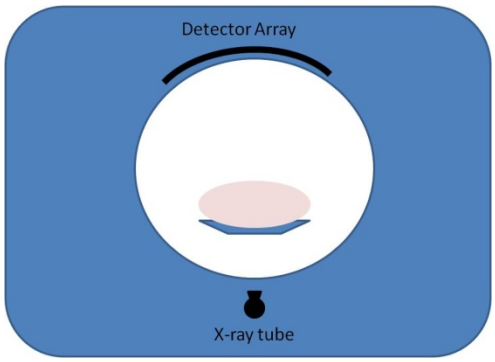
Answer: D – 2000

Explanation: Tissue A is bone. The CT number of bone is 1000. Tissue B is air with a CT number of −1000. The variation in CT number between the two tissues in Figure 8 is 2000 HU. (NOTE: HU and CT number are synonymous.)

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 356.
2. Seeram, E. *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. St. Louis: Saunders, 2009, p. 92–96.

Q9. The automatic exposure control system on a CT scanner determines the tube current for a particular scan based on a planning view (scout) image acquired with the tube stationary under the patient's bed. If the patient centerline is positioned below scanner isocenter, which of the following will be reduced?



A. spatial resolution
B. low-contrast visibility
C. image noise
D. patient dose

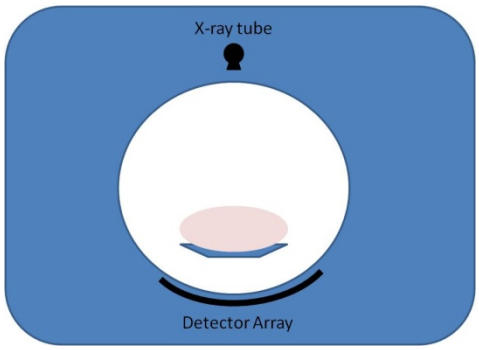
Answer: C – image noise

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, resulting in the scanner choosing a higher tube current in the automatic exposure control mode. Higher tube current will result in less image noise and, therefore, increased low-contrast visibility. Patient dose will increase proportionally with increased tube current. Spatial 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, p.233–234.

Q10. The automatic exposure control system on a CT scanner determines the tube current for a particular scan on a planning view (scout) image acquired with the tube stationary over the patient's bed. If the patient centerline is positioned below scanner isocenter which of the following will increase?



A. spatial resolution
B. low-contrast visibility
C. image noise
D. patient dose

Answer: C – image noise

Explanation: With the tube stationary over the patient and the patient positioned below isocenter for the acquisition of the scout view, the patient will appear smaller than actual size, resulting in the scanner choosing a lower tube current in the automatic exposure control mode. Lower tube current will result in more image noise and, therefore, decreased low-contrast visibility. Patient dose will decrease proportionally with increased tube current. Spatial resolution will not be affected by a change in tube current.

Module 15: Ultrasound

After completing this module, participants should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Identify common terms 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. Understand the definitions of axial, lateral, and elevational resolution. Describe the factors affecting spatial and temporal resolution, including multiple focal zones.
6. Identify common artifacts seen in ultrasound.
7. Describe the Doppler principle and its applications in various Doppler imaging modes. Explain aliasing and other Doppler-related artifacts.
8. Understand the principles of advanced ultrasound technologies, such as harmonic imaging, extended field of view, compound imaging, 3D/4D ultrasound, and ultrasound contrast agents.
9. Delineate the mechanisms for producing ultrasound bioeffects, and describe the significance of the parameters MI and TI.

Clinical Application:

1. Describe the relationship between ultrasound image formation and the resulting images.
2. Describe how scanner settings affect the clinical image and how to adjust the scan parameters to optimize image quality for different clinical applications.
3. Describe appropriate indications when advanced ultrasound technologies, such as harmonic imaging, extended field of view, compound imaging, 3D and 4D ultrasound, and ultrasound contrast agents, should be used in clinical imaging.
4. Discuss the accuracies of distance measurements with respect to scanning orientation.

Clinical Problem-solving:

1. Explain how to improve image quality during ultrasound imaging.
2. Explain the causes of ultrasound imaging artifacts and Doppler aliasing. Discuss how to reduce such artifacts, and explain how to use imaging effects and artifacts for diagnosis.
3. Describe the ultrasound parameters related to ultrasound bioeffects and safety.
4. Discuss risks versus benefits of using ultrasound in various clinical areas, especially in obstetrics.

Concise Syllabus:

15. Ultrasound
    - 15.1. Basic Physics of Ultrasound
    - 15.2. Transducer Fundamentals
    - 15.3. Beam-forming
    - 15.4. Image Resolution Measures
        - 15.4.1. Axial
        - 15.4.2. Longitudinal
        - 15.4.3. Elevational/Azimuthal
    - 15.5. Ultrasound Imaging Machines for Pulse-echo Imaging

15.5.1. Controls ("Knobology")
15.5.2. Image Data Acquisition
15.5.3. Image Processing and Display
15.6. Topics of Clinical Applications in Ultrasound Imaging
15.6.1. Ultrasound Contrast Agents
15.6.2. Compound Imaging
15.6.3. Harmonic Imaging
15.6.4. 3D Imaging
15.6.5. Time-dependent (4D) Imaging
15.7. Doppler Ultrasound Measurements and Flow Imaging
15.8. Artifacts
15.9. Safety and Bioeffects

Detailed Curriculum:

15. Ultrasound
15.9. Sound Wave Propagation
15.9.1. Definition of Sound and Ultrasound
15.9.2. Properties of Longitudinal as Compared to Transverse Waves
15.10. Sound Wave Properties
15.10.1. Wavelength, Frequency, Period, Speed, and Velocity
15.10.2. Density and Pressure Changes in Materials
15.10.3. Particle Motion and Particle Velocity
15.10.4. Compressibility and Elasticity
15.10.5. Dependence of Sound Speed on Medium and Properties
15.11. Power and Intensity
15.11.1. Decibel Scale
15.11.2. Relationship between Intensity and Pressure
15.12. Interactions of Ultrasound Waves with Matter
15.12.1. Acoustic Impedance
15.12.1.1. Relationship to Density, Speed, and Compressibility
15.12.1.2. Impedance Changes at Tissue Interfaces
15.12.2. Attenuation and Absorption
15.12.2.1. Causes and Relationship to Sound Properties
15.12.2.2. Attenuation as Compared to Absorption Coefficients
15.12.2.3. Typical Attenuation in the Body
15.12.3. Reflection, Refraction, and Transmission
15.12.3.1. Role of Impedance
15.12.3.2. Reflection Coefficient
15.12.3.3. Normal and Oblique Incidence
15.12.3.4. Specular and Diffuse Reflection
15.12.3.5. Transmission
15.12.3.6. Refraction and Snell's Law
15.12.4. Scattering
15.12.4.1. Hyperechoic and Hypoechoic Regions
15.12.4.2. Relationship to Frequency and Scatterer Size
15.12.4.3. Rayleigh Scattering
15.12.4.4. Constructive and Destructive Interference
15.12.4.5. Speckle

15.13. Transducer Components
- 15.13.1. Piezoelectric Materials
- 15.13.2. Capacitive Micro-machined Ultrasonic Transducers (C-MUT)
- 15.13.3. Transducer Construction
  - 15.13.3.1. Electronics
  - 15.13.3.2. Matching Layers
  - 15.13.3.3. Backing Block

15.14. Transducer Arrays
- 15.14.1. Linear and Curvilinear Arrays
- 15.14.2. Phased Arrays
- 15.14.3. Annular Arrays
- 15.14.4. 1.5D and 2D Arrays

15.15. Special-purpose Transducer Assemblies
- 15.15.1. Intra-cavitary Transducers
- 15.15.2. IVUS Transducers

15.16. Beam properties
- 15.16.1. The Near Field
- 15.16.2. The Far Field
- 15.16.3. Focused Transducers
- 15.16.4. Side and Grating Lobes

15.17. Transducer Array Beam Formation and Focusing
- 15.17.1. Linear and Sector Scanning
- 15.17.2. Transmit Focusing
- 15.17.3. Receive Focusing
- 15.17.4. Beam Steering
- 15.17.5. Beam Shaping

15.18. Resolution
- 15.18.1. Axial
- 15.18.2. Lateral
- 15.18.3. Elevational (Slice Thickness)
- 15.18.4. Temporal
- 15.18.5. Image Contrast

15.19. Pulse-echo Imaging
- 15.19.1. Method
- 15.19.2. Timing
  - 15.19.2.1. Pulse-repetition Frequency
  - 15.19.2.2. Pulse-repetition Period
- 15.19.3. Field of View and Maximum Depth
- 15.19.4. Frame Rate

15.20. Image Data Acquisition
- 15.20.1. Signal Acquisition
- 15.20.2. Pre-amplification and Analog to Digital Conversion
- 15.20.3. Time-Gain (or Depth-Gain) Compensation
- 15.20.4. Logarithmic Compression
- 15.20.5. Demodulation and Envelope Detection
- 15.20.6. Rejection
- 15.20.7. Processed Signal

15.21. Image Processing and Display

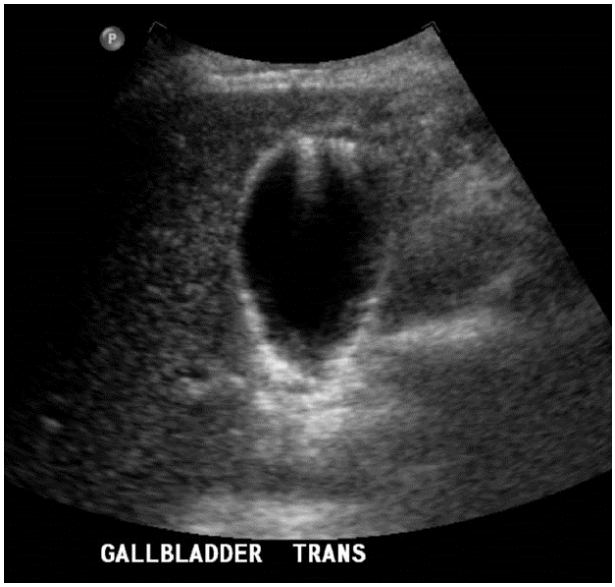
15.21.1. Display Modes
15.21.1.1. A-Mode
15.21.1.2. B-Mode
15.21.1.3. M-Mode
15.21.2. Image Frame-Rate Dependencies
15.21.2.1. Depth Setting
15.21.2.2. Transmit Focal Zones
15.21.2.3. Sector Size and Line Density
15.21.3. Image Display
15.21.3.1. Pre-processing and Post-processing
15.21.3.2. Noise and Speckle Reduction
15.21.3.3. Read Zoom and Write Zoom
15.21.4. Distance, Area, and Volume Measurements
15.22. Ultrasound Contrast Agents
15.23. Elastography
15.24. Compound Imaging
15.25. Harmonic Imaging
15.25.1. Nonlinear Propagation and Origin of Harmonics
15.25.2. Formation of Harmonics in Ultrasound
15.25.3. Advantages and Disadvantages
15.25.4. Narrow-band Harmonic Imaging
15.25.5. Pulse-Inversion Harmonic Imaging
15.25.6.
15.26. Three-dimensional (3D) Imaging
15.26.1. Image Reconstruction and Registration
15.27. Time-dependent Imaging (4D)
15.28. Doppler Ultrasound
15.28.1. Doppler Theory
15.28.2. Spectral Analysis
15.28.3. Continuous Wave (CW) Doppler
15.28.4. Pulsed Doppler
15.28.4.1. Pulse Transmission and Range Gating
15.28.4.2. Aliasing
15.28.5. Duplex Scanning
15.28.6. Color Flow Imaging
15.28.7. Power Doppler
15.29. Artifacts
15.29.1. Refraction
15.29.2. Shadowing and Enhancement
15.29.3. Reverberation
15.29.4. Speed Displacement
15.29.5. Comet Tail
15.29.6. Side and Grating Lobes
15.29.7. Multipath Reflection and Mirror Image
15.29.8. Range Ambiguity
15.29.9. Mirror Artifact
15.29.10. Doppler and Color Flow Aliasing
15.29.11. Flow Ambiguity

15.30. Safety and Bioeffects
- 15.30.1. Mechanisms for Producing Bioeffects
  - 15.30.1.1. Heating
  - 15.30.1.2. Cavitation
  - 15.30.1.3. Direct Mechanical
- 15.30.2. Acoustic Power
  - 15.30.2.1. Variation with Focus and Output Setting
  - 15.30.2.2. Pulse Repetition Frequency
  - 15.30.2.3. Transducer Frequency
  - 15.30.2.4. Operation Mode
- 15.30.3. Intensity Measures of Ultrasound Energy Deposition
  - 15.30.3.1. Spatial Average/Temporal Average Intensity [I(SATA)]
  - 15.30.3.2. Spatial Peak /Temporal Average Intensity [I(SPTA)]
  - 15.30.3.3. Spatial Peak/Pulse Average Intensity [I(SPPA)]
  - 15.30.3.4. Spatial Peak/Temporal Peak Intensity [I(SPTP)]
- 15.30.4. Real-time Acoustical Output Labeling
  - 15.30.4.1. Thermal Indices (TI and TIx)
  - 15.30.4.2. Mechanical Index (MI)
- 15.30.5. Pregnant Patient and Pediatric Protocols
  - 15.30.5.1. Acceptable TIB and TIC limits
  - 15.30.5.2. Current Clinical Statements on Ultrasound Safety

15.31. Phantoms and Tests for Ultrasound Quality Control and Quality Assurance

Example Q&A:

Q1. What is the artifact in this image with Adenomyomatosis clinical condition?



A. mirror image artifact
B. reverberation artifact
C. comet tail or ring down artifact

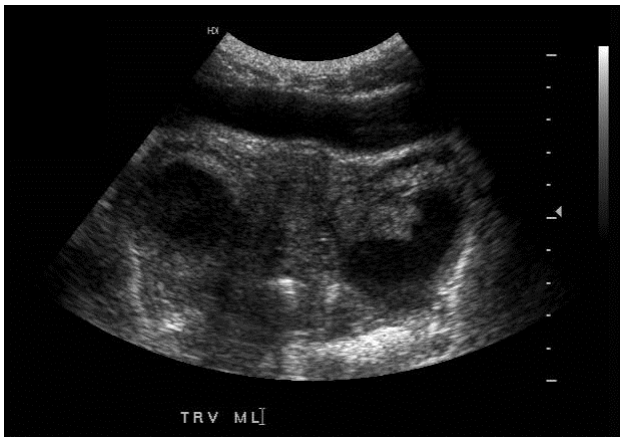
Answer: C – comet tail or ring down artifact

Explanation: Adenomyomatosis is a diseased state of the gallbladder in which the gallbladder wall is excessively thick. Ultrasonography may reveal the thickened gallbladder wall with intramural diverticulae, called Rokitansky-Aschoff sinuses. In the imaging part, when there is a serious mismatch in impedance, reverberations from highly reflective interface create short bands called comet tails. On the other hand, when a small gas volume (bubble) resonates, a continuous emission of ultrasound is produced, resulting in ring down artifact. (No bands are seen in this case.)

References:

1. Hedrick, P., et al. *Ultrasound Physics and Instrumentation*, 4th ed. Mosby, 2005.
2. Owen, C.C., L.E. Bilhartz. "Gallbladder polyps, cholesterolosis, adenomyomatosis, and acute acalculous cholecystitis." *Semin. Gastrointest. Dis.* 14:178–88, 2003.

Q2. What is the name of the artifact seen with bowel gas?



A. comet tail
B. mirror image
C. dirty shadowing, or dirty acoustic shadowing

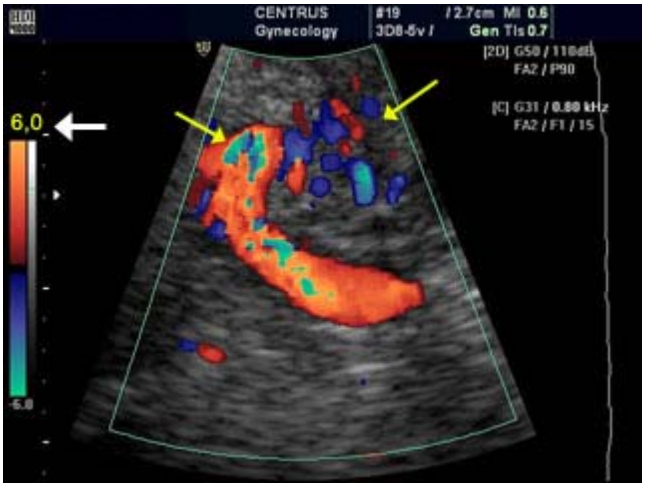
Answer: C – dirty shadowing or dirty acoustic shadowing

Explanation: Dirty shadowing is caused by scattering from many structures (interfaces) that are smaller than the wavelength of the ultrasound beam.

Reference:

1. Hedrick, P., et al. *Ultrasound Physics and Instrumentation*, 4th ed. Mosby, 2005.

Q3. What is the name of the artifact that occurs when the Doppler sampling rate is less than twice the Doppler frequency shift? (Hint: this artifact causes the high-frequency components to wrap around from the positive extreme of the scale to the negative extreme.)



A. aliasing
B. mirror image
C. reverberation

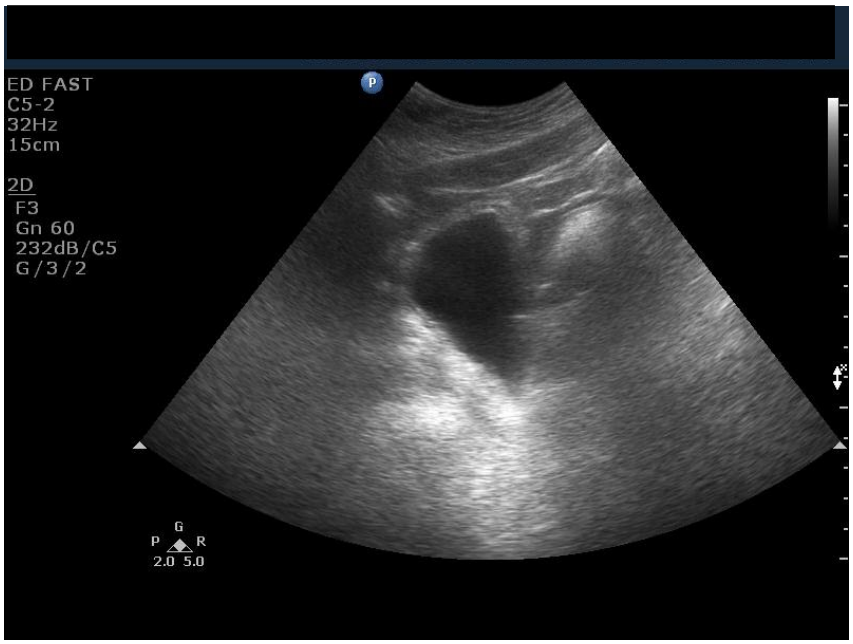
Answer: A – aliasing

Explanation: In the pulsed Doppler imaging, sampling rate or pulse repetition frequency (PRF) is set by the sonographer. Sampling rate (PRF) must be at least twice the maximum frequency shift present and is the Nyquist criterion. One half of the PRF is called Nyquist frequency limit (PRF of at least 20 Khz is required for a Doppler shift of 10 Khz). Doppler shifts above the Nyquist frequencies are displayed as a low-frequency shift—an artifact. Some ways to avoid this artifact include moving the color baseline up or down, increasing the velocity scale, etc.

References:

1. Kruskal, J.B., P.A. Newman, L.G. Sammons, R.A. Kane. "Optimizing Doppler and color flow US: application to hepatic sonography. *Radiographics* 24:657–75, 2004.
2. Hedrick, P., et al. *Ultrasound Physics and Instrumentation*, 4th ed. Mosby, 2005.

Q4. A simple cyst is defined as an anechoic structure with imperceptible walls and what property illustrated here? (Hint: this occurs because fluid-containing structures attenuate sound much less than solid structures)



A. shadowing
B. posterior enhancement
C. refraction

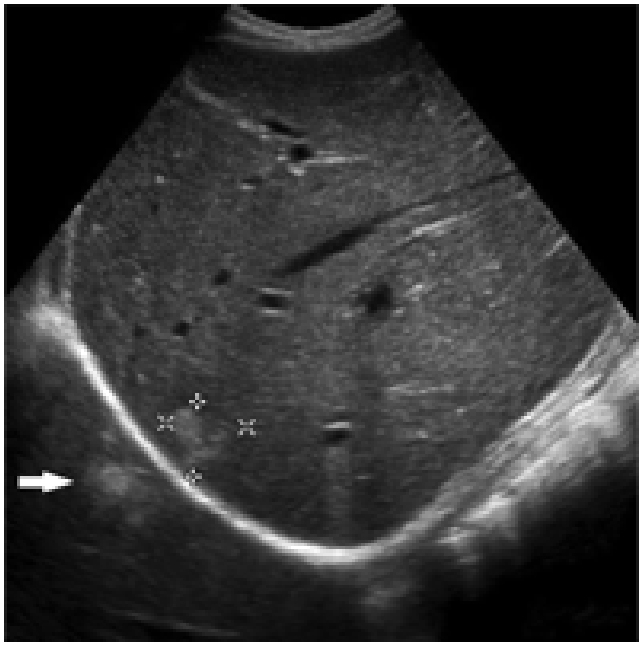
Answer: B – posterior enhancement

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 the produces a brighter echo, which is posterior enhancement.

Reference:

1. Hedrick, P., et al. *Ultrasound Physics and Instrumentation*, 4th ed. Mosby, 2005.

Q5. This ultrasound image has an artifact with the arrow pointing to it. Name this artifact.



A. mirror-image artifact
B. ring artifact
C. banding artifact

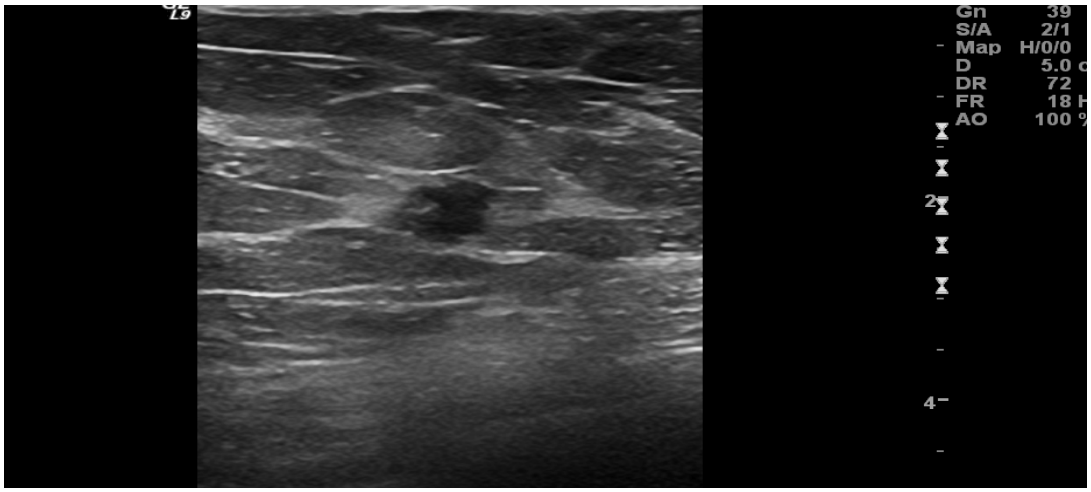
Answer: A – mirror-image artifact

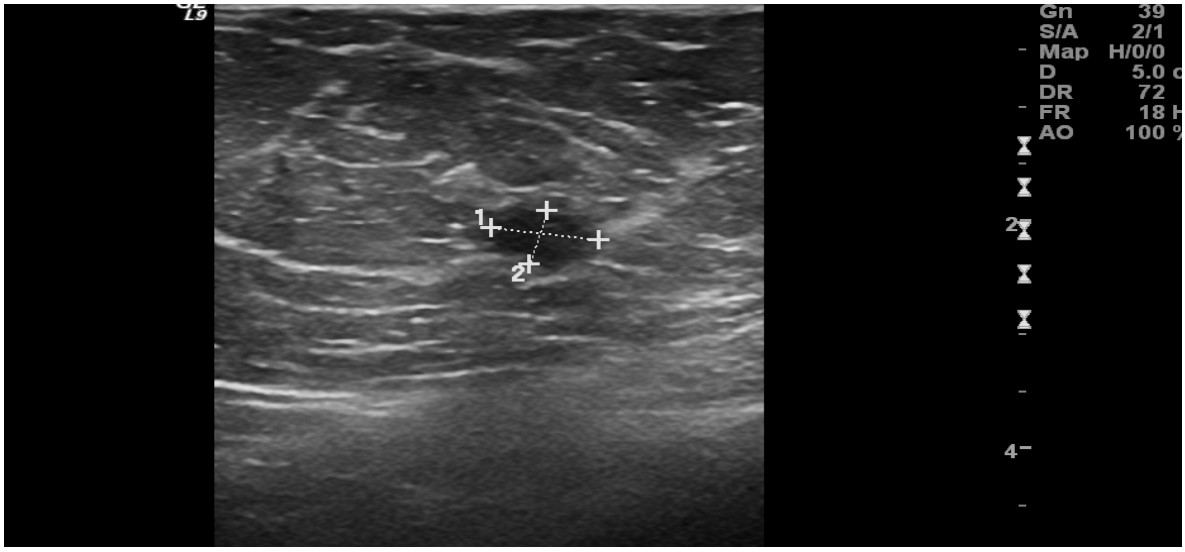
Explanation: Structures located in front of highly reflective surfaces may scatter sound off-axis. There is also the possibility of reverberation. The delayed arrival of these signals is interpreted as a mirror image at a deeper location by the recording device.

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.

Q6. In the two ultrasound images below, the top image is done without harmonics, and the bottom image is done with harmonics. The result is to achieve _____:





A. enhancement in spatial resolution
B. enhanced contrast
C. Doppler shift

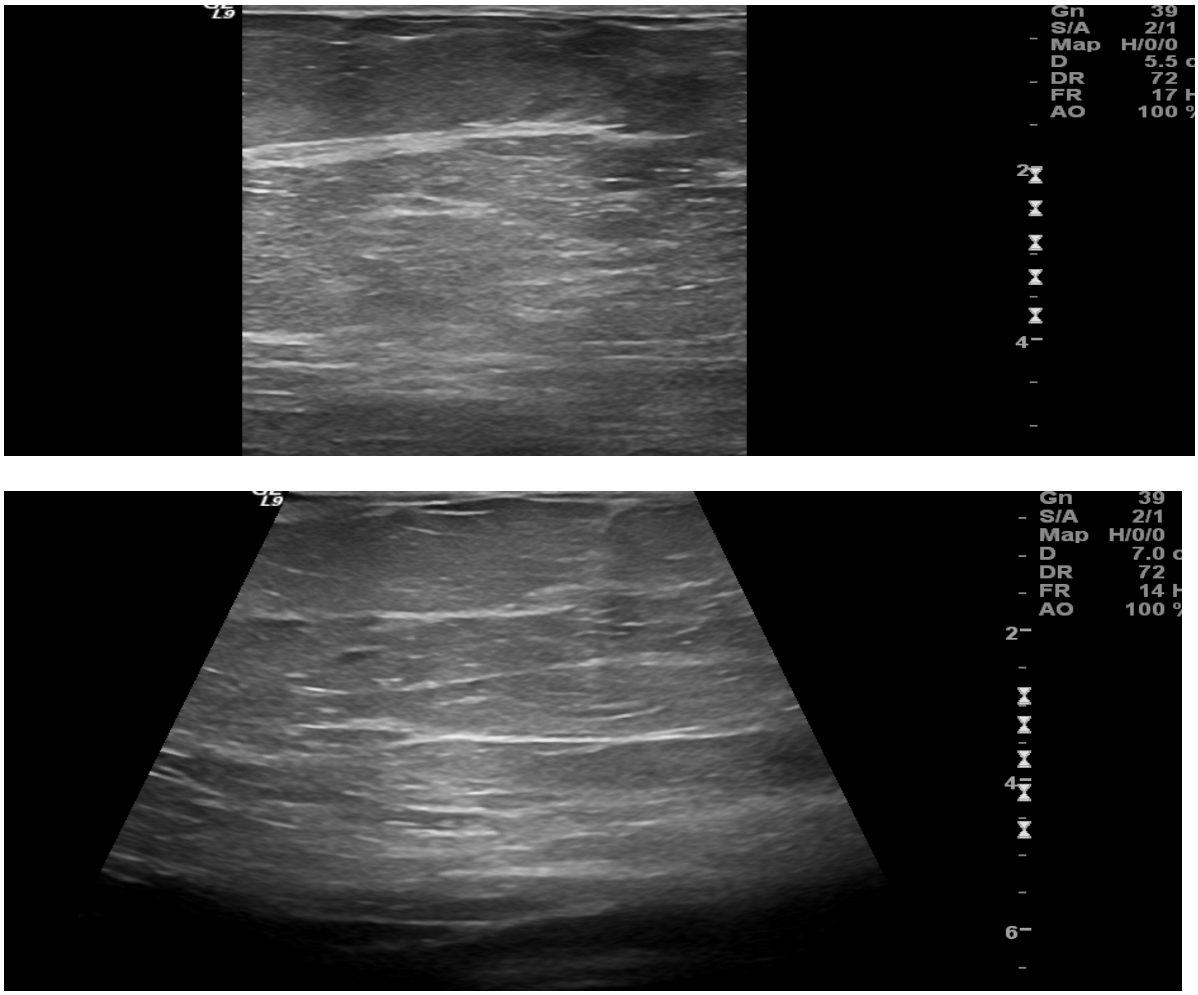
Answer: B – enhanced contrast

Explanation: When ultrasound waves interact with the tissue, different tissues distort the wave differently. (For example, fat distorts more than muscle or liver or kidney). The resultant wave has a harmonic frequency, which is selectively listened by the transducer receiver. The ultrasound system generates a high-contrast image with improved spatial resolution and with less artifact components.

Reference:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002.

Q7. Body habitus and transducer selection play key roles in ultrasound imaging. In the images below, the selection of a curvilinear transducer instead of a linear transducer gives _____.



A. better image depth
B. better resolution
C. more field of view

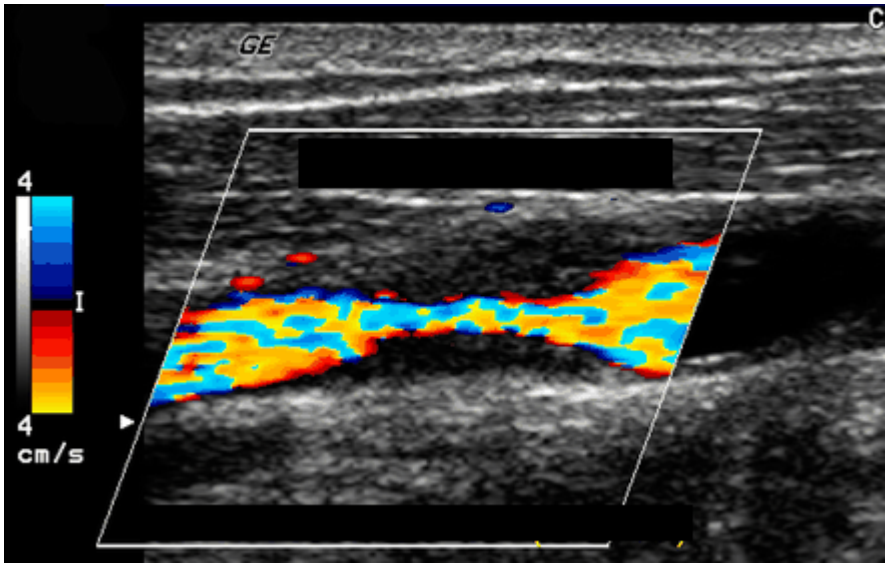
Answer: C – more field of view

Explanation: Curved-array transducers have a large field of view, better penetration of soft tissue, as well in this situation.

Reference:

1. Kruskal, J.B., P.A. Newman, L.G. Sammons, R.A. Kane. "Optimizing Doppler and color flow US: application to hepatic sonography." *Radiographics* 24:657–75, 2004.

Q8. How can the artifact shown in this image be corrected?



A. adjustment of the color Doppler threshold
B. adjustment of the color scale
C. adjustment of the color gain
D. adjustment of the sample volume angle to align with the wall contour of the ICA

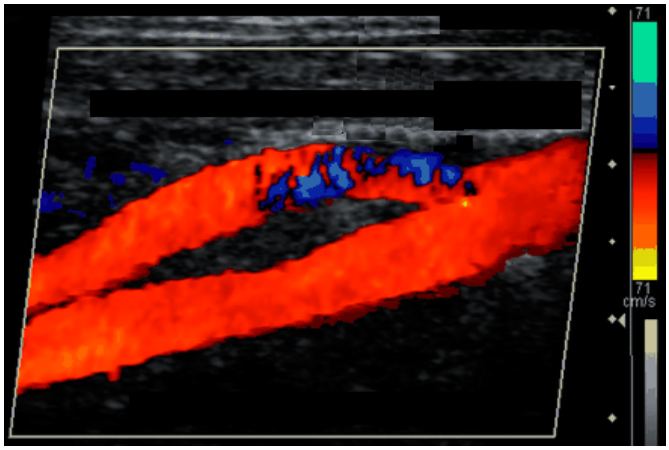
Answer: B – adjustment of the color scale

Explanation: This is an aliasing artifact. Adjustment of the color scale alters the velocity range that is displayed and is, therefore, used to prevent aliasing.

Reference:

1. Kruskal, J.B., P.A. Newman, L.G. Sammons, R.A. Kane. "Optimizing Doppler and color flow US: application to hepatic sonography." *Radiographics* 24:657–75, 2004.

Q9. For a better evaluation of the ECA on the Doppler study shown below, what should be adjusted?



A. color Doppler sampling window
B. color scale
C. color gain
D. sample volume angle to be aligned with the wall contour of the ICA

Answer: A – the color Doppler sampling window

Explanation: The color Doppler image shows that the leftward position of the color Doppler sampling window results in a poor Doppler angle of incidence to the direction of blood flow in the proximal ECA. The result of an angle of incidence of almost 90° is ambiguous color display in this segment of the ECA.

Reference:

1. Kruskal, J.B., P.A. Newman, L.G. Sammons, R.A. Kane. "Optimizing Doppler and color flow US: application to hepatic sonography." *Radiographics* 24:657–75, 2004.

Q10. Using Doppler to interrogate a vessel demands using the correct angle. An angle of ____ degrees is usually preferred to obtain accurate velocity measurements.

A. 80
B. 65
C. 60
D. 30

Answer: C – 60

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

References:

1. Kruskal, J.B., P.A. Newman, L.G. Sammons, R.A. Kane. "Optimizing Doppler and color flow US: application to hepatic sonography." *Radiographics* 24:657–75, 2004.

Module 16: MRI

After completing this module, the resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Describe the properties of magnetism and how materials react to and interact with magnetic fields.
2. Describe how the magnetic resonance signal is created.
3. Describe magnet designs and typical magnetic field strengths employed for clinical imaging.
4. Define the physical properties of a material that determine the MR signal.
5. Compare the basic pulse sequences used to produce contrast between tissues in MRI.
6. List the components of an MR system and how they are used.
7. Describe how spatial localization is achieved in MRI.
8. Review the principles of *k*-space generation and describe how to "fill *k*-space" to optimize signal strength (signal-to-noise ratio) or acquisition time.
9. Describe how T1, T2, proton density, and T2* contrast can be achieved in MRI.
10. Explain how secondary tissue properties like diffusion, perfusion, and flow can be distinguished in MRI.
11. Distinguish between phase contrast, 2D, and 3D time of flight MRA.
12. Review the important concepts of functional MRI.
13. Review the important concepts of MR spectroscopy.
14. Describe the types of contrast agents used in MR and how they affect the signal relative to the pulse sequence used.
15. Describe the concept of partial saturation and how it affects the signal acquired.
16. Recognize how MRI acquisition techniques can be made to provide unique physiologic and anatomic information or decrease the image acquisition time.
17. Identify the source and appearance of MRI artifacts.
18. Review the safety and bioeffects of concern in MR systems.
19. Summarize the issues related to planning the installation of an MR system and the concerns for ancillary equipment and persons in the areas around an MR site.

Clinical Application:

1. Determine how the magnetic properties of a material affect the overall signal obtained in an MR image.
2. Identify the most appropriate pulse sequences for a specific diagnostic task.
3. Describe contrast-induced nephropathy and methods to reduce risk of such an outcome.
4. Describe the risks and benefits when MR imaging is used on a pregnant patient.
5. Discuss clinical situations in which MRI should be requested over alternative diagnostic procedures.
6. Discuss clinical situations in which MRI procedures are contra-indicated.

Clinical Problem-solving:

1. Estimate how the installation of different hardware (e.g., different field strength system) might change the acquisition parameters and image quality in MRI.
2. Analyze how a change in the acquisition parameters affects the resulting MR image.
3. Determine the source of an artifact, and describe a change or changes to the acquisition parameters to reduce the appearance of the artifact.

4. Describe common clinical artifacts and methods for reducing or eliminating these artifacts in an MRI scan, including: motion, chemical shift, gradient non-linearity, aliasing, Gibbs ringing, radiofrequency interference, susceptibility, and local B_0 field non-uniformities.

Concise Syllabus:

16. MRI
    - 16.11. Fundamental Magnetic Properties and Physics
    - 16.12. Basic Magnetic Resonance Imaging
        - 16.12.1. RF Pulses for Echo Formations
        - 16.12.2. Gradient Coils and Timing for Image Formation
        - 16.12.3. 2D Image Formation by Fourier Transform from Spin Echoes
        - 16.12.4. Basic Spin-echo Pulse Sequence
        - 16.12.5. Basic Inversion-recovery Sequence
        - 16.12.6. Basic Gradient-echo Sequences
        - 16.12.7. Fast (Turbo) Spin-echo Sequences
        - 16.12.8. Echo-planar Imaging Sequences
        - 16.12.9. Tradeoffs among Spatial Resolution, SNR, and Acquisition Time
    - 16.13. MRI Contrast Mechanisms and Contrast Agents
        - 16.13.1. Spin Density
        - 16.13.2. T1 Weighting
        - 16.13.3. T2 Weighting
        - 16.13.4. T2* Weighting
        - 16.13.5. Effects of Exogenous Contrast Agents
    - 16.14. MRI Instrumentation
        - 16.14.1. Static Magnetic Field (B_0) System
        - 16.14.2. Gradient Field Subsystem
        - 16.14.3. Shim Coils
        - 16.14.4. RF Transmitter (B_1) Subsystem
        - 16.14.5. RF Receiver Subsystem
        - 16.14.6. RF Coils
    - 16.15. Additional Acquisition Techniques
        - 16.15.1. Flow Compensation
        - 16.15.2. Selective Tissue Suppression
        - 16.15.3. Angiography
        - 16.15.4. Diffusion and Perfusion Imaging
        - 16.15.5. Magnetization Transfer Contrast
    - 16.16. Artifacts
    - 16.17. Safety and Bioeffects

Detailed Curriculum:

16. Magnetic Residence Imaging
    - 16.1. Magnetism and Magnetic Fields
        - 16.1.1. Magnetic Susceptibility
        - 16.1.2. Types of Magnetic Materials (e.g., Diamagnetic, Paramagnetic, Super-Paramagnetic and Ferromagnetic)
        - 16.1.3. Magnetic Fields (B)
            - 16.1.3.1. Units for Magnetic Field Strength
            - 16.1.3.2. Magnetic Dipole

16.1.3.3. Magnetic Moment
16.1.3.4. Nuclear Magnetism (Protons and Biologically Relevant Nuclei)
16.1.4. Magnetic Moment Interaction with an External Field (B_0)
16.1.4.1. Alignment (Low-energy and High-energy States)
16.1.4.2. Precession
16.1.4.3. Larmor Equation and Frequency
16.1.4.4. Rotating Versus Laboratory Frames of Reference
16.1.5. Net Magnetization Due to B_0
16.1.5.1. Equilibrium Magnetization (M_0)
16.1.5.2. Longitudinal Magnetization (M_z)
16.1.5.3. Transverse Magnetization (M_{xy})
16.1.5.4. Proton Density (Spin-density)
16.1.5.5. Field Strength Dependence
16.2. Nuclear Magnetic Resonance and Excitation
16.2.1. Radiofrequency (RF) field (B_1)
16.2.2. Flip Angle
16.2.3. Free-induction Decay (FID)
16.2.4. 90^0 and 180^0 RF Pulses
16.3. Magnetic Resonance Signal Properties
16.3.1. Spin Density (Proton-oriented)
16.3.2. T2 (Transverse) Relaxation
16.3.2.1. Intrinsic Spin-spin Interactions
16.3.2.2. Transverse Magnetization Decay
16.3.2.3. Typical Tissue T2 Values
16.3.3. T2* Relaxation
16.3.3.1. Dependence on Field Inhomogeneity
16.3.3.2. Susceptibility Induced Dephasing (e.g., Tissue-air Interfaces)
16.3.4. T1 (Longitudinal) Relaxation
16.3.4.1. Spin-lattice Interactions
16.3.4.2. Longitudinal Recovery
16.3.4.3. Typical Tissue T1 values
16.3.4.4. Field-strength Dependence
16.4. Pulse Sequences and Contrast Mechanisms
16.4.1. Spin-echo (SE) Pulse Sequence
16.4.1.1. Pulse Sequence Basics (Timing Diagrams)
16.4.1.2. Echo Time (TE)
16.4.1.3. Repetition Time (TR)
16.4.1.4. SE Signal Intensity Dependence on TE and TR
16.4.1.5. SE Contrast (T1, Proton Density, T2-Weighted)
16.4.2. Inversion-recovery Spin-echo Pulse Sequence
16.4.2.1. Inversion Time (TI)
16.4.2.2. Short (Inversion) Time Inversion-recovery (STIR)
16.4.2.3. Fluid-Attenuated Inversion-recovery (FLAIR)
16.4.3. Gradient-echo Pulse Sequence
16.4.3.1. Advantages and Disadvantages, Compared to SE Sequence
16.4.3.2. Gradient-echo, Signal-intensity, and Effect of Flip Angle
16.4.3.3. Cumulative Phase Correction by Crusher Gradient and RF-Pulse Spoiling
16.4.3.4. Gradient Echo Contrast (T2*/T1, T2*, and T1–Weighting)

16.4.4. Echo-Planar (EPI)
16.4.4.1. Single-shot Method
16.4.4.2. Multi-shot Method
16.4.4.3. T2* Contrast
16.4.5. Fast or Turbo Spin-echo
16.4.5.1. Echo Train Length
16.4.5.2. Echo Spacing
16.4.5.3. Effective TE
16.4.5.4. Contrast (T2 and T1 Weighting)
16.4.5.5. Introduction to Phase Reordering
16.4.6. Specifications of Pulse Sequences
16.4.6.1. Acquisition Time Calculations
16.4.6.2. Multi-slice Acquisition
16.4.6.3. 2D and 3D Acquisitions
16.4.6.4. Timing Diagrams
16.4.6.5. Flow Compensation Methods
16.5. MR Instrumentation
16.5.1. Static Magnetic Field (B_0) Systems
16.5.1.1. Types of Magnets
16.5.1.2. Fringe Field
16.5.1.3. Main Magnetic Field Shielding (Fringe Field Reduction)
16.5.2. Gradient Field Subsystem
16.5.2.1. Gradient Coil Geometry (X,Y, and Z)
16.5.2.2. Gradient Strength (mT/m)
16.5.2.3. Slew-Rate: Specification (mT/m/s), Eddy Currents, and Effects on Gradient Performance
16.5.2.4. Compensation for Effects of Eddy Currents
16.5.3. Shim Coils
16.5.3.1. B_0 Inhomogeneity Compensation
16.5.3.2. Passive and Active Shim Types
16.5.3.3. Overview of Shim Geometry
16.5.4. RF Transmitter (B_1) Subsystem
16.5.4.1. RF-pulse Bandwidth
16.5.4.2. Control of Flip Angle
16.5.5. RF Receiver Subsystem
16.5.5.1. Receiver Gain Controls
16.5.5.2. Digital Sampling of Received Signals
16.5.5.2.1. Analog-to-digital Converter (ADC) Sampling
16.5.5.2.2. Other Data Acquisition Elements
16.5.5.3. Receive Bandwidth and Filters
16.5.5.4. Parallel (and Phased-array) Receive Channels
16.5.6. RF Coils
16.5.6.1. Transmit-and-receive Coils
16.5.6.2. Volume vs. Surface Coils
16.5.6.3. Receive-only Coils
16.5.6.4. Quadrature vs. Linear Coils
16.5.6.5. Birdcage Coils
16.5.6.6. Phased-array Coils

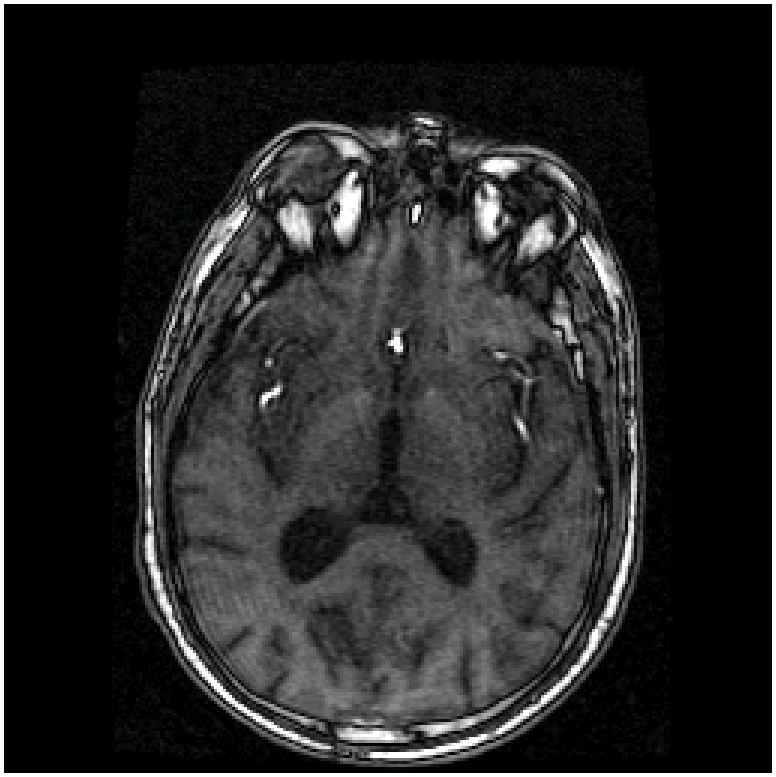
16.5.6.7. Parallel Imaging (e.g., SENSE) Coils
16.6. Spatial Localization
16.6.1. Slice-selection
16.6.2. Phase-encoding
16.6.3. Frequency-encoding
16.7. Two-dimensional Fourier Transform (2DFT) Image Reconstruction
16.7.1. *k*-Space Description
16.7.2. Methods of "Filling *k*-Space"
16.7.2.1. Rectangular
16.7.2.2. Spiral
16.7.2.3. Radial
16.7.2.4. Fractional
16.7.2.5. EPI Phase Reordering
16.8. Image Characteristics
16.8.1. Factors Affecting Spatial Resolution
16.8.1.1. Field-of-view (FOV)
16.8.1.2. Sampling Bandwidth
16.8.1.3. Slice Thickness
16.8.1.4. Image Matrix Dimensions
16.8.2. Factors Affecting Signal-to-noise Ratio (SNR)
16.8.2.1. Voxel Size
16.8.2.2. Signal Averages
16.8.2.3. Receiver (Sampling) Bandwidth
16.8.2.4. Magnetic Field Strength
16.8.2.5. Slice "Cross-Talk"
16.8.2.6. Reconstruction Algorithms
16.8.2.7. RF Coil Quality Factor (Q)
16.8.2.8. Pulse Sequence Specific Effects
16.8.2.9. Surface Coil B_1 Homogeneity Corrections
16.8.2.10. Parallel Imaging Acceleration Factors
16.8.2.11. Saturation and Flow
16.8.3. Tradeoffs among Spatial Resolution, SNR, and Acquisition Time
16.8.4. Factors Affecting Image Contrast
16.8.4.1. Proton Density, T1, T2
16.8.4.2. Susceptibility
16.8.4.3. Appearance of Blood and Blood Products
16.9. Contrast Agents
16.9.1. Paramagnetic
16.9.2. Other Susceptibility Agents
16.9.3. Contrast Nephropathy
16.10. Saturation Methods and Effects
16.10.1. Spatial
16.10.2. Chemical (e.g., Fat, Silicone)
16.11. Special Acquisition Techniques
16.11.1. Angiography
16.11.1.1. Effect of Blood Flow on Signal Intensity
16.11.1.2. Time-of-flight (2D and 3D) Techniques
16.11.1.3. Phase-contrast Techniques

16.11.1.4. Contrast-agent Enhanced MRA Techniques
16.11.2. Diffusion, Perfusion, and Neuro Imaging
16.11.2.1. Basic Principles
16.11.2.2. Diffusion-weighted Imaging (DWI) Techniques
16.11.2.3. Apparent Diffusion Coefficient (ADC)
16.11.2.4. Diffusion-tensor Imaging (DTI) Techniques
16.11.2.5. Neural Tractography Applications
16.11.3. Functional MRI (fMRI)
16.11.3.1. Blood Oxygen-level Dependent (BOLD) Principles
16.11.3.2. Clinical Applications
16.11.4. Magnetization Transfer Contrast (MTC)
16.11.4.1. Basic Principles
16.11.4.2. Contrast Mechanisms
16.11.4.3. Clinical Applications
16.11.5. Parallel MRI
16.11.5.1. Basic Principles
16.11.5.2. Image-based Implementation
16.11.5.3. *k*-Space-based Implementation
16.11.6. Proton Spectroscopy
16.11.6.1. Basic Principles
16.11.6.2. Single Voxel Techniques
16.11.6.3. Chemical-shift Imaging (CSI), 2D and 3D
16.11.6.4. Water Suppression
16.11.6.5. Importance of TE and TR Values
16.11.6.6. Clinical Applications
16.12. Artifacts
16.12.1. Metal and Susceptibility Artifacts
16.12.2. Gradient-field and Static-field Inhomogeneity Artifacts
16.12.3. Radiofrequency Artifacts
16.12.4. *k*-Space Errors
16.12.5. Motion Artifacts
16.12.6. Chemical Shift Artifacts (Fat/Water)
16.12.7. Gibbs (Ringing, Truncation) Artifacts
16.12.8. Aliasing (Wraparound)
16.12.9. Partial-volume Artifacts
16.12.10. High-speed Imaging Artifacts (e.g., Echo-planar Distortion, Ghosting)
16.12.11. Effect of High Field Strength on Artifacts
16.13. Safety and Bioeffects
16.13.1. Static Magnetic Field
16.13.1.1. Biological Effects
16.13.1.2. Projectile Hazards
16.13.1.3. Effects on Implanted Devices
16.13.1.4. FDA Limits
16.13.2. RF Field
16.13.2.1. Biological Effects, e.g., Tissue Heating and Other
16.13.2.2. RF Heating of Conductors and Potential Burns
16.13.2.3. Specific Absorption Rate (SAR)
16.13.2.4. High Field Strength System Issues

16.13.2.5. FDA Limits
16.13.3. Gradient Field
16.13.3.1. Biological Effects, Including Peripheral Nerve Stimulation
16.13.3.2. Sound Pressure Level ("Noise") Issues and Limits
16.13.3.3. FDA Limits
16.13.4. Contrast Agent Safety Issues
16.13.5. Screening Patients and Healthcare Workers
16.13.6. MR Safety Systems and Superconducting Magnet "Quench" Systems
16.13.7. Cryogenic Materials
16.13.8. Current Risk vs. Benefit Guidance for Pregnant Patients and Staff
16.13.9. "MR Safe" and "MR Compatible" Equipment and Devices
16.14. Magnet System Siting
16.14.1. Basic Facility Design and Safety Zone Design
16.14.2. Magnetic Fringe Field and the 0.5 mT (5G) Line
16.14.3. Magnetic Field Shielding
16.14.4. RF Field Shielding
16.14.5. Effects of MRI on Other Equipment and Objects
16.14.6. Effects of Equipment and Objects on MRI
16.15. Accreditation, Quality Control (QC), and Quality Improvement
16.15.1. Components of an ACR MRI Accreditation Program
16.15.2. Quality Control Phantoms and Measurements
16.15.3. Quality Improvement Program Considerations

Example Q&A:

Q1. What artifact is present in this MR image?



A. patient motion
B. aliasing
C. truncation
D. flow artifacts

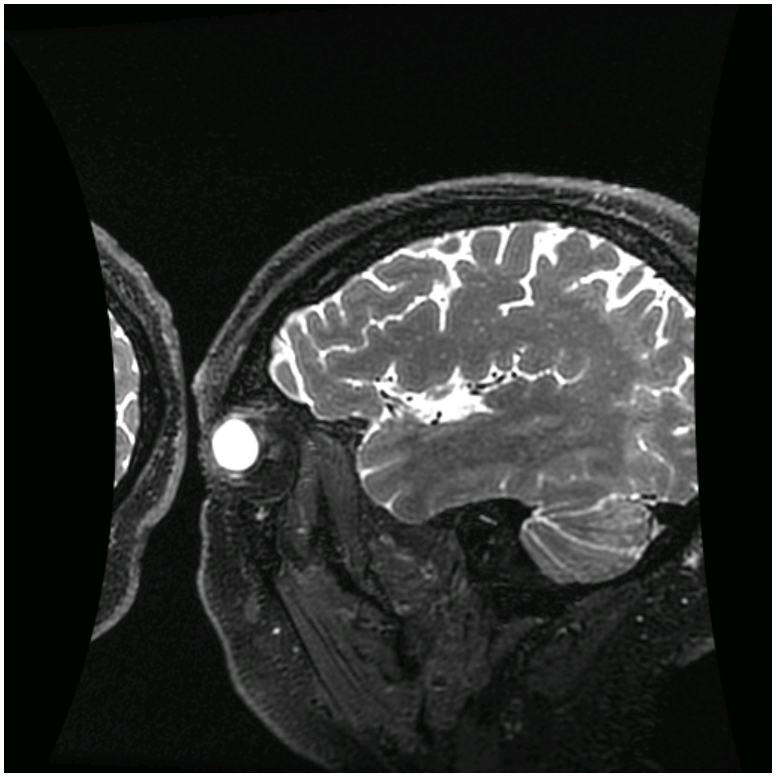
Answer: C – truncation artifacts

Explanation: Truncation artifacts are also known as Gibbs-ringing artifacts. They typically present as multiple parallel lines adjacent to high-contrast interfaces. Those artifacts come from using a finite number of sampling points in the frequency or phase-encoding direction in the image acquisition. The Fourier transform of a signal will result in overshoot and undershoot oscillations (ringing) when a sharp border is encountered in the image. The ringing could happen in both the frequency and phase directions. However, it is commonly seen in the phase direction since phase step usually is reduced to save scan time. The solution for this artifact is to increase the imaging matrix, which usually will increase scan time and reduce SNR.

References:

1. Elster, A.D. and J.H. Burdette. *Questions and Answers in Magnetic Resonance Imaging*, 2nd ed. St. Louis: Mosby, 2001, p. 142.
2. 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, p. 580.

Q2. Which of the following techniques will you use to remove the aliasing artifacts without changing spatial resolution or scan time in the figure below, a high-resolution T2W sagittal image? Orbits are the subject.



A. increase FOV
B. increase FOV and matrix size
C. reposition the patient to make the orbits at the center of the FOV
D. use anti-aliasing technique, such as No Phase Wrapping

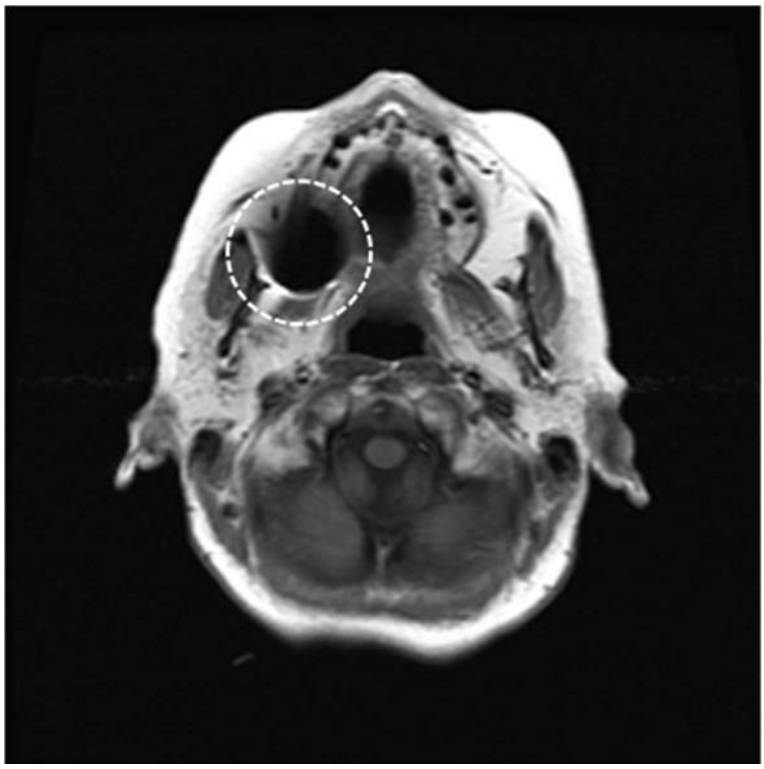
Answer: D – use anti-aliasing technique to remove artifacts and preserve high-resolution image.

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 has to be at least twice that of the highest frequency expected, $f_{aliased} = f_{true} - 2f_{Nyquist}$. 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 with the cost of spatial resolution. An anti-aliasing technique, such as No Phase Wrapping, is achieved by doubling the number of phase encodes, which is equivalent to having 2x FOV, but only the original FOV is displayed, using partial Fourier reconstruction to keep almost the same scan time. Aliasing artifacts could happen in the Z-direction if 3D technique is used.

References:

1. Elster, A.D. and J.H. Burdette. *Questions and Answers in Magnetic Resonance Imaging*, 2nd ed. St. Louis: Mosby, 2001, p. 149.
2. 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, p. 578.

Q3. Which of the following techniques could be used to reduce this artifact?



A. gradient echo sequence
B. spin echo sequence
C. increase TE, decrease receiver bandwidth
D. short TE, increased bandwidth
E. both B and D

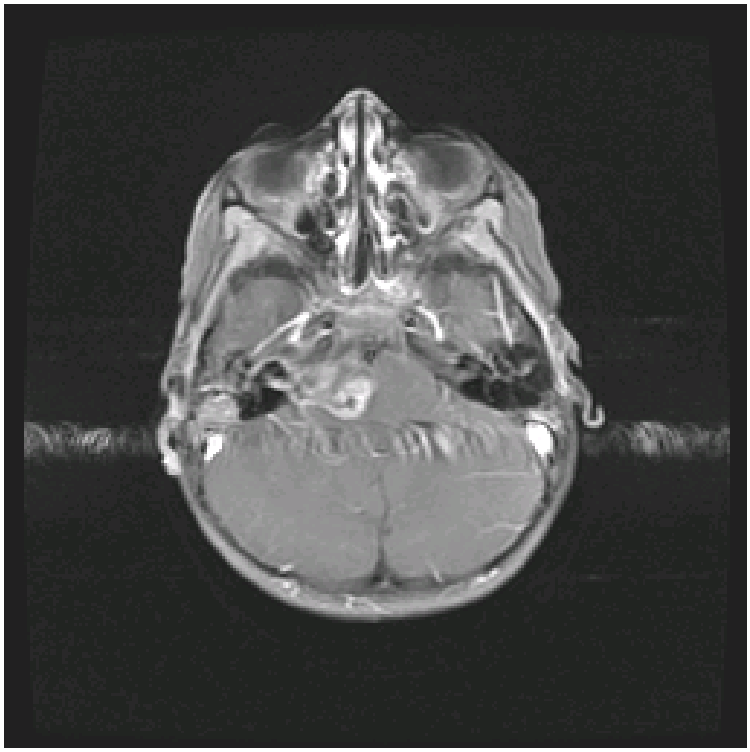
Answer: E – both B and D – Using spin echo (SE) sequence with shorter TE and higher receiver bandwidth

Explanation: This is a clinical brain image showing susceptibility artifact (teeth filling). Magnetic susceptibility of metal differs from that of surrounding tissue, causing local distortion of magnetic field, causing more rapid spin dephasing. 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. Short TE and wider receive bandwidth also help to reduce susceptibility artifacts.

References:

1. Elster, A.D. and J.H. Burdette. *Questions and Answers in Magnetic Resonance Imaging*, 2nd ed. St. Louis: Mosby, 2001, p. 57.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 391–405.

Q4. What artifact is present in the following MRI image?



A. motion artifact
B. flow artifact
C. RF interference artifact
D. gradient failure artifact

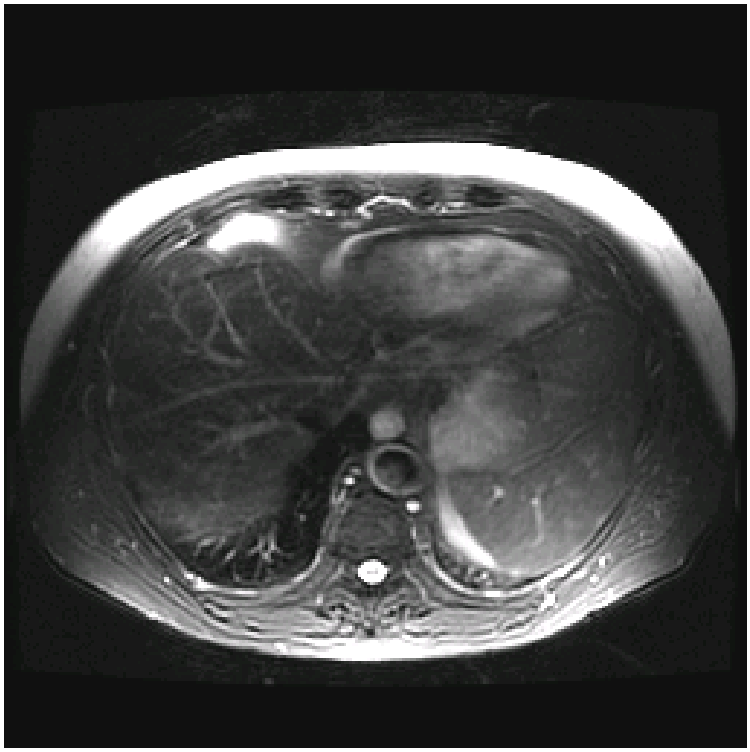
Answer: B – flow artifact

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.

Reference:

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, p. 587.

Q5. What is the most likely interpretation of the following MR image?



A. T1W abdominal image
B. T1W abdominal image with poor fat suppression and some breathing artifacts
C. T2W abdominal image with poor fat suppression and some breathing artifacts
D. T2W abdominal image

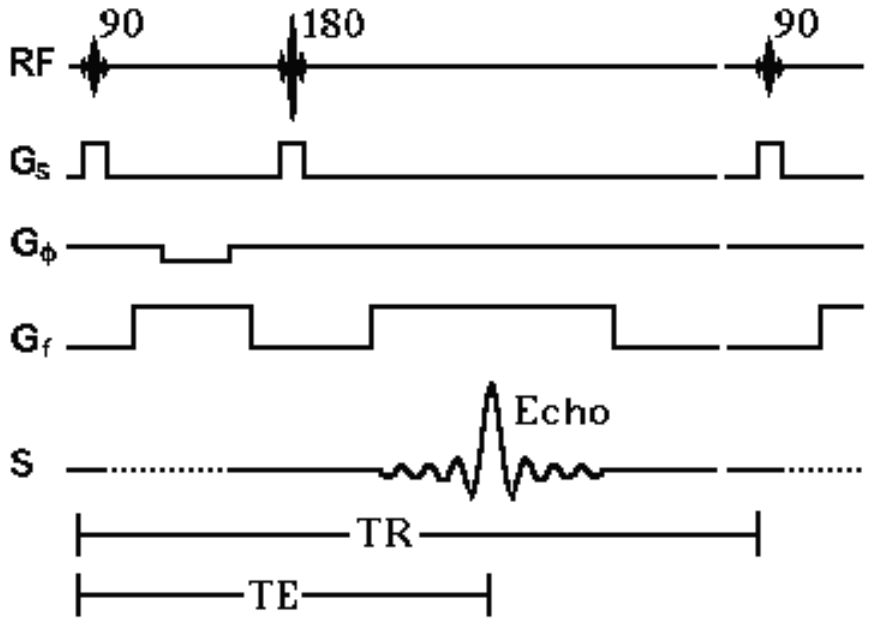
Answer: C – T2W abdominal image with poor fat suppression and some breathing artifacts

Explanation: First, this is a T2W image, since the CSF in the cord and other fluid is bright. Second, fat suppression is used, except it does not work at the top of the image. This situation happens often in the clinic when a patient is big and chemical fat suppression is used with phased array coils. To reduce non-uniform fat suppression, apply shimming and use special spectral RF pulse for fat suppression. The Dixon method can be used if it is available. A STIR-type sequence could be used with the cost of scan time and SNR. Breathing artifacts can be reduced with respiratory triggering if patient breathing is regular, otherwise use breath hold method.

Reference:

1. Elster, A.D. and J.H. Burdette. *Questions and Answers in Magnetic Resonance Imaging*, 2nd ed. St. Louis: Mosby, 2001, p. 210–217.

Q6. The figure below is a MR pulse sequence timing diagram. What pulse sequence is it?



A. spin echo (SE) sequence
B. gradient echo (GRE) sequence
C. fast spin echo (FSE) sequence
D. echo Planar Imaging (EPI) sequence

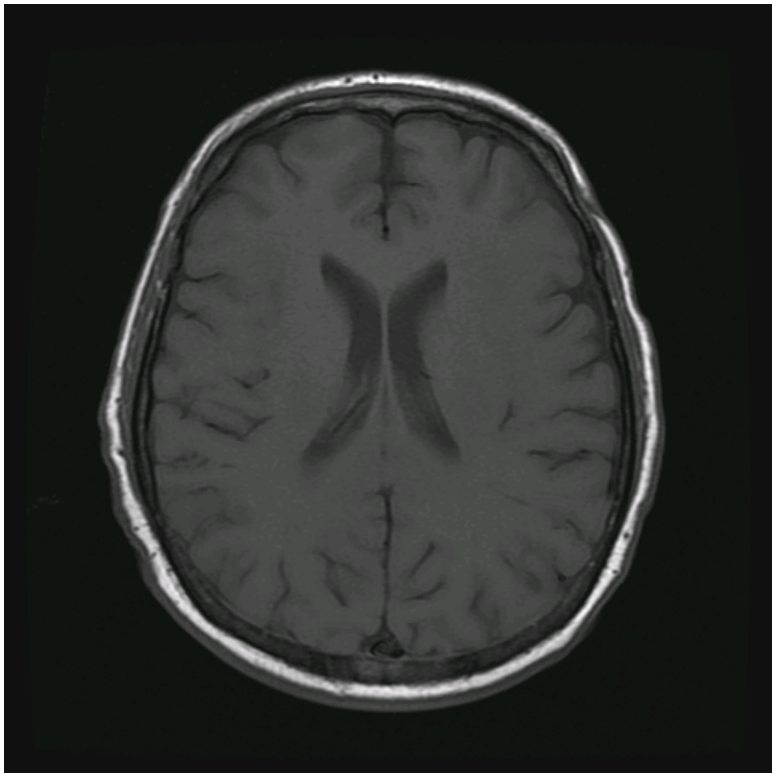
Answer: A – a spin echo sequence.

Explanation: (SE) is the most common pulse sequence used in MR imaging. It is based the detection of a spin (or Hahn) echo. It uses one 90° RF pulse to excite spins and one 180° RF pulse to refocus the spins to generate signal echoes named spin echoes. Of course, there are slice selection and refocusing gradients, and frequency encoding and phase encoding gradients to complete the imaging acquisition. Many pulse sequences are developed based on SE.

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, p. 32.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 391–395.

Q7. Although spin echo sequence is kind of slow, it is still a classic MRI technique generating good image contrast with minimal artifacts. Which of the following parameters can be combined to generate T1-weighted brain image using spin echo sequence on 1.5T system?



A. TR = 100 msec, TE ~10 msec
B. TR = 400–600 msec, TE ~10 msec
C. TR ≥ 2000 msec, TE ~10 msec
D. TR ≥ 2000 msec, TE ≥ 80 msec

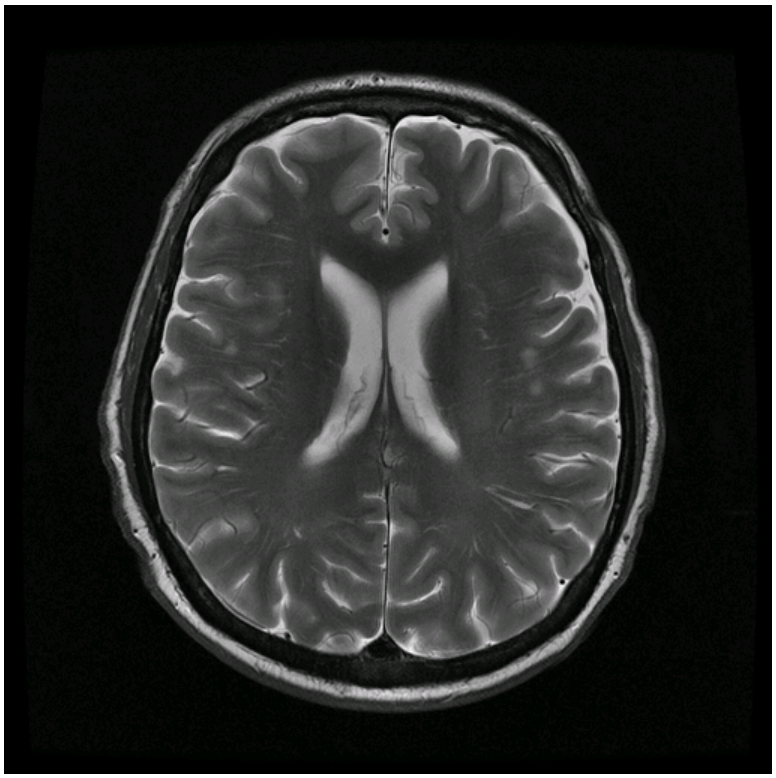
Answer: B – TR between 400 msec and 600 msec

Explanation: For spin echo sequence, TR primarily controls the amount of T1-weighting, whereas TE primarily controls the amount of T2-weighting. The signal is proportional to $(1-\exp(-TR/T1)) \times \exp(-TE/T2)$. Therefore, a relatively short TR and very short TE should be used (so that the T2 effect can be ignored) to generate T1W image. There is no "best TR," but rather a range to produce T1-weighting, depends on the tissue being imaged and the field strength. For a 1.5T system, TR between 400–600 msec and a very short TE generate a good T1W brain 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, p. 30.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 395–396.

Q8. The following figure shows a T2W brain image. Which of the following parameters can be combined to generate T2-weighted brain image using spin echo sequence?



A. TR = 100 msec, TE ~10 msec
B. TR = 400- 600 msec, TE ~10 msec
C. TR ≥ 2000 msec, TE ~10 msec
D. TR ≥ 2000 msec, TE ≥ 80 msec

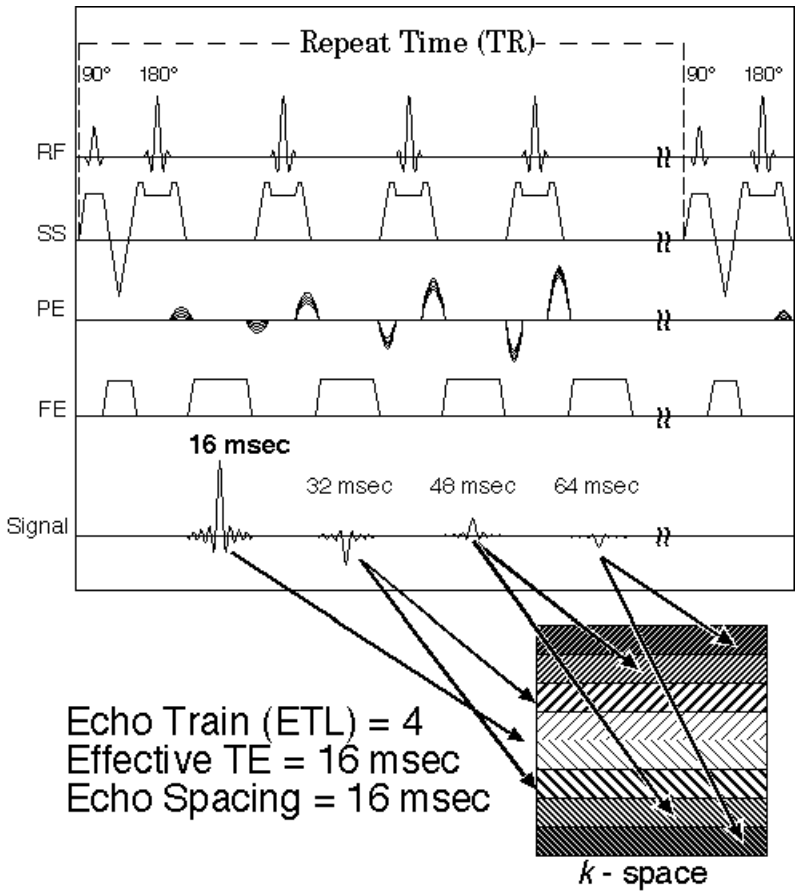
Answer: D – TR ≥ 2000 msec, and TE ≥ 80 msec

Explanation: As pointed out in the previous question, the signal in spin echo sequence is proportional to $(1 - \exp(-TR/T1)) \times \exp(-TE/T2)$. Therefore, a long TR (≥2000 msec) will make the T1 term negligible. And long TE (≥80 msec) enhances the brain tissue's T2 contrast. CSF has the longest T2 value comparing to other brain tissues, such as GM and WM, therefore CSF is very bright in the T2W image. Since 180 RF pulse can reverse the spin dephasing from magnetic field inhomogeneity, SE sequence is not able to produce T2* weighted 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, p. 30.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p. 397–398.

Q9. The figure below is a fast spin echo (FSE) sequence timing diagram, with 4 echo train length (ETL) plotted and an example of how the k-space is filled. For a 256 x 256 image, SE acquisition takes 4 minutes. How long will it take for this FSE acquisition?



A. 4 min.
B. 8 min.
C. 1 min.
D. 16 min.

Answer: C –1 min

Explanation: SE sequence can only acquire one echo per one repetition time; that means one k-space line is filled in one TR. To increase acquisition speed, multiple 180 RF pulses are inserted at certain times so that multiple echoes can be generated in one TR. In this way, multiple lines of k-space are filled in one TR. The figure has four ETL played out, which means that four k-space lines can be filled in one TR. To fill 256 (phase values) k-space lines, it will take 16 (256/4) TRs to scan one image, so the scan time is reduced to one quarter of the original SE acquisition.

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, p. 35.

Q10. Assume an MRI image is acquired by the FSE sequence diagrammed in the figure above where TR = 500 msec. What image contrast will it most likely generate?

A. T1W
B. T2W
C. Proton density weighted (PD)
D. T2* weighted

Answer: A – T1W.

Explanation: First of all, T1W, T2W, and PD images can be generated by FSE sequence. The figure above has 4 echo train length. The first echo fills the center of the k-space. The effective TE = 16 msec (corresponding to location of the first echo). Since TR = 500 msec, an image with T1W contrast will be generated. To generate a T2W image, long TR and long TE should be used. In that case, usually long ETL (>12) is more efficient. T2* weighted image can't be generated by FSE 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, p. 34.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, p.432.

Module 17: Nuclear Medicine

After completing this module, the radiology resident should be able to apply the "Fundamental Knowledge" and "Clinical Applications" learned from the module to example tasks, such as those found in "Clinical Problem-solving."

Fundamental Knowledge:

1. Describe the structure of matter, modes of radioactive decay, particle and photon emissions, and interactions of radiation with matter.
2. Describe the instrumentation, major components, and principles of operation for instruments commonly used for detecting, measuring, and imaging radioactivity.
3. Describe the instrumentation and software required for image generation and display.
4. Describe instrumentation and software QC tests and test frequencies.
5. Describe the factors that affect image quality.
6. Describe radionuclide production and the principles of radiochemistry.
7. Identify established radiopharmaceuticals, the indications for use, and appropriate adult and pediatric dosages.
8. Describe radiopharmaceutical QC tests and test frequencies.
9. Describe the methods of determining organ dose and whole body dose to patients and care givers.
10. Describe probability distributions, nuclear counting statistics, and statistics applicable to nuclear imaging.
11. Demonstrate a working knowledge of computational image processing, quality control of image acquisition, and processing.
12. Identify the elements of radiation biology and cell biology applicable to risk and radionuclide uptake and distribution in nuclear medicine.
13. Describe the required radiation protection practices for implementing laboratory tests, diagnostic imaging procedures, and therapeutic applications of radiopharmaceuticals.

Clinical Application:

1. Explain and discuss for each organ system the advantages, disadvantages, indications, and contraindications for each radiopharmaceutical used in imaging and therapeutic procedures.
2. Discuss the need for and importance of clinical history prior to performing radioisotope imaging and therapeutic procedures.
3. Explain how radioisotope imaging supports staging disease, determining residual or recurrent disease, assessing response to and monitoring of therapy, and providing prognostic information.
4. Explain how each imaging study or each therapeutic procedure can affect patient management.
5. Explain how various disease processes (e.g., malignant, metabolic, infectious, etc.) can be evaluated by each imaging agent.
6. Explain how to determine the radiopharmaceutical activity administered to adults and pediatric patients for various imaging procedures.

Clinical Problem-solving:

1. Evaluate images for quality and artifacts, and explain the causes of each artifact.
2. Describe the appropriate imaging order for multiple examinations (e.g., x-ray, US, CT, MRI, and NM) ordered on a patient.
3. Discuss the impact that contrast agents used in non-nuclear imaging procedures have on the nuclear medicine image.

4. Determine the period of time a lactating patient should be instructed to cease breastfeeding following a radioisotope imaging or therapeutic procedure.
5. Evaluate the risk of performing a nuclear imaging procedure on a pregnant patient. Which isotopes cross the placenta and which isotopes do not?
6. Perform organ dose and external dose calculations for two Tc-99m compounds, an intermediate-energy and a high-energy isotope used in routine nuclear medicine imaging and therapy.
7. Analyze the radiation dose from a nuclear medicine procedure and correlate the radiation risks to the potential benefit.
8. Determine when a nuclear medicine procedure should not be performed.

Concise Syllabus:

17. Nuclear Medicine
    - 17.1. Radioactivity: Definition, Units, Decay Equation, Half-life.
    - 17.2. Nuclear Transformation
    - 17.3. Radioactive Equilibrium
    - 17.4. Radioisotope Production
    - 17.5. Radionuclide Generators
    - 17.6. Radiopharmaceuticals
    - 17.7. Radiation Detection Instrumentation
    - 17.8. Scintillation Cameras
        - 17.8.1. Camera Design and Characteristics
        - 17.8.2. Collimators
        - 17.8.3. Image Acquisition and Processing
        - 17.8.4. Measures of Performance
        - 17.8.5. Artifacts
    - 17.9. Clinical Imaging
        - 17.9.1. Imaging Various Organs
        - 17.9.2. Clinical Considerations: Adult, Pediatric, Pregnancy, Breastfeeding
    - 17.10. SPECT Imaging
    - 17.11. PET Imaging
    - 17.12. Fusion Imaging: PET/CT, SPECT/CT
    - 17.13. Nuclear Medicine Therapy
    - 17.14. Safety: Patient, Staff, Public
    - 17.15. Training and Experience for Authorized Users of Radioactive Materials.
    - 17.16. Radiation Doses

Detailed Curriculum:

17. Nuclear Medicine
    - 17.1. Radionuclide Decay
        - 17.1.1. Radioactivity
            - 17.1.1.1. Definition
            - 17.1.1.2. Units
            - 17.1.1.3. Decay Constant
            - 17.1.1.4. Decay Equation
            - 17.1.1.5. Half-life (Physical, Biological and Effective)
        - 17.1.2. Nuclear Transformation

17.1.2.1. N/Z Ratio and Nuclear Stability
17.1.2.2. Beta (Negative Electron) Decay
17.1.2.3. Positron (Positive Electron) Decay
17.1.2.4. Electron Capture
17.1.2.5. Isomeric Transition
17.1.2.6. Alpha Decay
17.1.2.7. Internal Conversion
17.1.2.8. Nuclear Fission
17.1.3. Radioactive Equilibrium
17.1.3.1. Transient
17.1.3.2. Secular
17.2. Radioisotope Production
17.2.1. Linear Accelerator and Cyclotron
17.2.2. Reactor
17.2.2.1. Fission Products
17.2.2.2. Neutron-Activation Products
17.2.3. Radionuclide Generators
17.2.3.1. $^{99}Mo - ^{99m}Tc$
17.2.3.2. Other (e.g., $^{82}Sr - ^{82}Rb$ PET)
17.2.3.3. Elution and Quality Control
17.3. Radiopharmaceuticals
17.3.1. Preparation
17.3.2. Range of Required Activities for Clinical Studies
17.3.3. Localization
17.3.4. Uptake, Distribution, and Decay
17.3.5. Quality Assurance and Quality Control Procedures
17.3.6. Internal Organ Dosimetry
17.3.7. Dose Rates from Radioactive Patients
17.4. Radiation Detection Instrumentation
17.4.1. Gas-filled Detectors
17.4.1.1. Mechanisms of Operation
17.4.1.2. Applications and Limitations
17.4.1.3. Survey Meters (e.g., GM Counter, Ionization Chamber)
17.4.1.4. Dose Calibrator
17.4.1.5. Quality Control
17.4.2. Scintillation Detectors
17.4.2.1. Mechanisms of Operation
17.4.2.2. Applications and Limitations
17.4.2.3. Pulse-height Spectroscopy
17.4.2.4. Thyroid Probe
17.4.2.5. Well Counter
17.4.2.6. Survey Meter
17.4.2.7. Quality Control
17.4.3. Other Types of Detectors
17.5. Scintillation Camera
17.5.1. Clinical Purpose
17.5.2. Camera Design
17.5.2.1. Crystal Parameters

17.5.2.2. Spatial Localization
17.5.2.3. Energy Discrimination
17.5.3. Collimator Characteristics
17.5.3.1. Sensitivity
17.5.3.2. Resolution
17.5.3.3. Energy
17.5.4. Collimators
17.5.4.1. Parallel-hole
17.5.4.2. Pinhole
17.5.4.3. Specialized
17.5.5. Image Acquisition
17.5.5.1. Static
17.5.5.2. Dynamic
17.5.5.3. Gated
17.5.5.4. List-mode
17.5.6. Image Processing
17.5.6.1. Subtraction
17.5.6.2. Region of Interest (ROI)
17.5.6.3. Time–Activity Curves
17.5.6.4. Spatial Filtering
17.5.6.5. Temporal Filtering
17.5.7. Measures of Performance (Extrinsic and Intrinsic)
17.5.7.1. Uniformity
17.5.7.2. Spatial Resolution
17.5.7.3. Energy Resolution
17.5.7.4. Spatial Linearity
17.5.7.5. Sensitivity
17.5.7.6. Count-rate Performance
17.5.7.7. Dead-time
17.5.8. Artifacts
17.5.8.1. Damaged or Broken Crystal
17.5.8.2. Nonuniformity
17.5.8.3. Bad Phototube
17.5.8.4. Improper Energy Peaking
17.5.8.5. Mechanical Separation of Coupling Elements
17.5.8.6. Damaged Collimators
17.5.8.7. Motion
17.5.8.8. Dual Isotope
17.5.8.9. Wrong Collimator Selection
17.5.9. Clinical Imaging
17.5.9.1. Thyroid
17.5.9.2. Bone
17.5.9.3. Renal
17.5.9.4. Liver/Spleen
17.5.9.5. Cardiac (Ejection Fraction, Myocardial Perfusion)
17.5.9.6. Ventilation Perfusion (VQ)
17.5.9.7. Multi-Energy Imaging
17.5.9.8. Tumor Imaging

17.7.15. Clinical Examples
17.8. Combined Modalities
17.8.1. SPECT/CT
17.8.1.1. Mechanisms of Operation
17.8.1.2. Clinical Applications
17.8.1.3. Quality Assurance and Quality Control
17.8.1.4. Artifacts
17.8.2. PET/CT
17.8.2.1. Mechanisms of Operation
17.8.2.2. Clinical Applications
17.8.2.3. Quality Assurance and Quality Control
17.8.2.4. Artifacts
17.9. Nuclear Medicine Therapy
17.9.1. Written Directive
17.9.2. Safety Considerations
17.10. Factors Affecting Public, Staff, and Unintended Patient Dose
17.10.1. Source Control (e.g., Patient Location)
17.10.2. Administered Pharmaceutical, Isotope and Activity
17.10.3. Contamination Control
17.10.4. Patient Flow
17.11. Patient Dose
17.11.1. MIRD

Example Q&A:

Q1. What is the mechanism of localization of Tc-99m MAA?

A. capillary blockade
B. diffusion
C. phagocytosis
D. sequestration

Answer: A – capillary blockade

Explanation: Tc-99m MAA particles are generally 10–30 micrometers in size and are too large to pass through the lung capillaries, which are generally 7–10 micrometers in diameter.

References:

1. Mettler, F.A., Jr. and M.J. Guiberteau. *Essentials of Nuclear Medicine Imaging*. 6th ed. Philadelphia: Elsevier Saunders, 2012.
2. Ziessman, H.A, J.P. O'Malley, and J.H. Thrall. *Nuclear Medicine: The Requisites*, 3rd ed. Mosby Elsevier, 2006.

Q2. What is the mechanism of localization of Tc-99m methylene diphosphonate (MDP)?

A. capillary blockade
B. chemisorption
C. diffusion
D. metabolism

Answer: B – chemisorption

Explanation: Tc-99m binds to the hydroxyapatite crystal component in the bone matrix by chemisorption**.**

References:

1. Mettler, F.A., Jr. and M.J. Guiberteau. *Essentials of Nuclear Medicine Imaging*. 6th ed. Philadelphia: Elsevier Saunders, 2012.
2. Ziessman, H.A, J.P. O'Malley, and J.H. Thrall. *Nuclear Medicine: The Requisites*, 3rd ed. Mosby Elsevier, 2006.

Q3. What is the mechanism of localization of I-123 sodium iodide in the thyroid gland?

A. active transport
B. diffusion
C. metabolism
D. receptor binding

Answer: A – active transport

Explanation: I-123 NaI is taken up by thyroid follicular cells by active transport by the thyroid pump (also known as the sodium iodide symporter). The I-123 NaI is then trapped and organified.

References:

1. Mettler, F.A., Jr. and M.J. Guiberteau. *Essentials of Nuclear Medicine Imaging*. 6th ed. Philadelphia: Elsevier Saunders, 2012.
2. Ziessman, H.A, J.P. O'Malley, and J.H. Thrall. *Nuclear Medicine: The Requisites*, 3rd ed. Mosby Elsevier, 2006.

Q4. What is the mechanism of localization of F-18 fluorodeoxyglucose (F-18 FDG)?

A. active transport
B. diffusion
C. compartmental localization
D. receptor binding

Answer: A – active transport

Explanation: F-18 FDG is an analog of glucose and is actively transported across the cell membrane by glucose transporters.

Reference:

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

Q5. Excessive Mo-99 in the Tc-99m pertechnetate eluate is an example of a problem with:

A. physical purity
B. radionuclidic purity
C. radiochemical purity
D. chemical purity

Answer: B – radionuclidic purity

Explanation: Any radionuclide in the Mo-99/Tc-99m eluate other than the Tc-99m is a radionuclidic impurity.

References:

1. Mettler, F.A., Jr. and M.J. Guiberteau. *Essentials of Nuclear Medicine Imaging*. 6th ed. Philadelphia: Elsevier Saunders, 2012.
2. Ziessman, H.A, J.P. O'Malley, and J.H. Thrall. *Nuclear Medicine: The Requisites*, 3rd ed. Mosby Elsevier, 2006.

Q6. What is the regulatory limit for the amount of Mo-99 per mCi of Tc-99m radiopharmaceutical at the time of administration?

A. 0.15 microcurie (uCi)
B. 0.5 uCi
C. 0.15 millicurie (mCi)
D. 0.5 mCi

Answer: A – 0.15 uCi by NRC regulation

Explanation: Mo-99 in the eluate will increase radiation dose without any benefit to the patient. Also, the half-life of Mo-99 (67 hours) is longer than that of Tc-99m (6 hours). Increasing the time between elution and administration of Tc-99m will cause degradation of the images.

References:

1. Mettler, F.A., Jr. and M.J. Guiberteau. *Essentials of Nuclear Medicine Imaging*. 6th ed. Philadelphia: Elsevier Saunders, 2012.
2. Ziessman, H.A, J.P. O'Malley, and J.H. Thrall. *Nuclear Medicine: The Requisites*, 3rd ed. Mosby Elsevier, 2006.

Q7. Too much aluminum in the Mo-99/Tc-99m eluate is an example of a problem with:

A. physical purity
B. radionuclidic purity
C. radiochemical purity
D. chemical purity

Answer: D – chemical purity

Explanation: Aluminum (as Al_2O_3, aluminum oxide) would be a chemical impurity in the eluate.
Physical purity: fraction of total pharmaceutical in the desired physical form.
Radionuclidic purity: fraction of total radioactivity in the form of the desired radionuclide.
Radiochemical purity: fraction of total radioactivity in the desired chemical form.
Chemical purity: fraction of wanted vs. unwanted chemical in the preparation.

References:

1. Mettler, F.A., Jr. and M.J. Guiberteau. *Essentials of Nuclear Medicine Imaging*. 6th ed. Philadelphia: Elsevier Saunders, 2012.
2. Ziessman, H.A, J.P. O'Malley, and J.H. Thrall. *Nuclear Medicine: The Requisites*, 3rd ed. Mosby Elsevier, 2006.

Q8. What is the regulatory limit of aluminum oxide (Al_2O_3) in the Mo-99/Tc-99m generator eluate?

A. <10 ug/ml
B. <20 ug/ml
C. <10 mg/ml
D. <20 mg/ml

Answer: A – <10 ug/ml by regulation.

Explanation: Aluminum oxide in the eluate will cause colloid formation and alter the uptake pattern of the radiopharmaceutical. Hepatic uptake can be seen with too much aluminum oxide in the radiopharmaceutical.

References:

1. Mettler, F.A., Jr. and M.J. Guiberteau. *Essentials of Nuclear Medicine Imaging*. 6th ed. Philadelphia: Elsevier Saunders, 2012.
2. Ziessman, H.A, J.P. O'Malley, and J.H. Thrall. *Nuclear Medicine: The Requisites*, 3rd ed. Mosby Elsevier, 2006.

Q9. What is the regulatory limit by the NRC for error between the indicated exposure rate and the calculated exposure rate for survey instruments?

A. 10%
B. 20%
C. 25%
D. 50%

Answer: B – 20%

Explanation: This is the regulatory limit per NRC regulations 10 CFR 35.61.

Reference:

1. Nuclear Regulatory Commission. 10CFR 35, Part 61 – Calibration of survey instruments. Available online at http://www.nrc.gov/reading-rm/doc-collections/cfr/part035/part035-0061.html .

Q10. How often should the dose calibrator be tested for accuracy?

A. weekly
B. monthly
C. quarterly
D. annually

Answer: D – annually

Explanation: Annually, which is the standard in nuclear medicine. The NRC had previously required an annual measurement for accuracy, although that requirement by the NRC was removed several years ago. This is still the industry standard, and the manufacturers still recommend annual calibration for accuracy.

References:

1. Ziessman, H.A, J.P. O'Malley, and J.H. Thrall. *Nuclear Medicine: The Requisites*, 3rd ed. Mosby Elsevier, 2006.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q11. How often should the dose calibrator be tested for constancy?

A. daily
B. weekly
C. monthly
D. quarterly

Answer: A - daily

Explanation: Constancy, or precision, should be tested daily, as per NRC regulations. This is still the industry standard, although the NRC removed these requirements several years ago.

References:

1. Ziessman, H.A, J.P. O'Malley, and J.H. Thrall. *Nuclear Medicine: The Requisites*, 3rd ed. Mosby Elsevier, 2006.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q12. How often should the dose calibrator be tested for linearity?

A. daily
B. weekly
C. monthly
D. quarterly

Answer: D – quarterly

Explanation: Testing should be done quarterly, as per NRC regulations. This is still the industry standard, although the NRC removed these requirements several years ago.

References:

1. Ziessman, H.A, J.P. O'Malley, and J.H. Thrall. *Nuclear Medicine: The Requisites*, 3rd ed. Mosby Elsevier, 2006.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Q13. A patient with a history of thyroid cancer has suspected bone metastases in the cervical spine. It is recommended to perform both an I-123 radioiodine scan as well as a bone scan using Tc99m MDP. Which would be the optimum sequence to perform unambiguous imaging in the shortest time?

A. Administer the I-123 and Tc-99m simultaneously. Perform the bone scan first and recall the patient after 24 hours for the radioiodine scan.
B. Administer the I-123 first. Perform the I-123 scan at 24 hours, and then inject Tc99m MDP and perform the bone scan at 4 hours.
C. Administer the I-123 first and scan at 24 hours. Ask the patient to wait for three days, and then administer the Tc99m and do the bone scan.
D. Administer the Tc-99m MDP first. Perform the bone scan. Then administer the I-123 and perform the thyroid workup after 24 hours.
E. Administer the Tc-99m MDP, followed shortly thereafter by the I-123. Perform the bone scan at 4 hours and the thyroid workup at 24 hours.
F. Administer the Tc-99m MDP first. Perform the bone scan. Have the patient return the next day and administer the I-123 and perform the thyroid workup after 24 hours.

Answer: F – Administer the Tc-99m MDP first. Perform the bone scan. Have the patient return the next day and administer the I-123 and perform the thyroid workup after 24 hours.

Explanation: Knowing the energies, half-lives, and typical activities of the radionuclides involved (Tc99m T ½ of 6.02 hours, energy 140 keV, and typical activity of approximately 20 mCi; I-123 T ½ of 13.2 hours, energy of 159 keV, and typical activity for thyroid cancer workup of 2 to 5 mCi), the sequencing for best imaging and minimum time may be determined. Since I-123 is higher energy, but overlapping with Tc99m, one would want to use it after the Tc99m imaging is done. Since the half-life of Tc is shorter, and I-123 imaging is done at 24 hours for thyroid cancer workup, the Tc99m MDP may be administered and imaging performed at 3 to 4 hours. However, at 24 hours the activity, accounting for 50% elimination, is approximately 300 mCi and bony visualization may occur. If the I-123 is administered the next day and imaged at 24 hours, which is now at 48 hours post Tc-99m, the activity of the Tc-99m at that time will less than 50 mCi and will not impact the thyroid imaging.

References:

1. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, Appendix F–2.
2. American College of Radiology. "ACR–SNM–SPR Practice Guideline for the Performance of Thyroid Scintigraphy and Uptake Measurement." On-line at http://interactive.snm.org/docs/Thyroid_Scintigraphy.pdf.

Q14. The source shown below would be used for:

A. daily check of survey meter
B. dose calibrator linearity
C. calibration of well counter
D. dose calibrator accuracy
E. intrinsic uniformity test of scintillation camera

Answer: D – dose calibrator accuracy

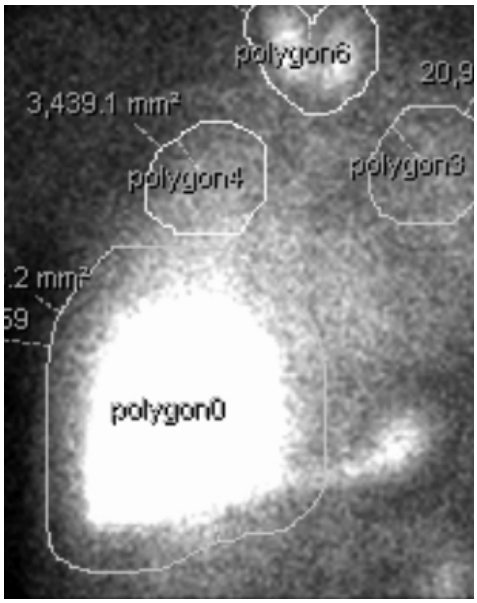
Explanation: The dose calibrator must have an accuracy test performed annually, using sources that are NIST traceable, such as the Vial E shown above. Note that in the image, the labeling shows that this is a reference source and that it is Cs-137. This source is likely also used for the daily constancy check. The

survey meter would use a point source that is attached to the meter. Linearity is performed with a clinical source of 30 to 200 millicuries, depending on the operation of the department. A well counter will use a much lower activity rod source, and either a Co57 flood source or a syringe with approximately 100 microcuries of activity will be used for camera QA.

References:

1. American Association of Physicists in Medicine. *AAPM Report 181: The Selection, Use, Calibration, and Quality Assurance of Radionuclide Calibrators Used in Nuclear Medicine*. College Park, MD: AAPM, 2012.
2. Bushberg, J.T., et al. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012, p. 665.

Q15. This Tc-99m macroaggregated albumin shunt study demonstrates:



A. radionuclidic impurity
B. chemical impurity
C. radiochemical impurity
D. pharmaceutical impurity

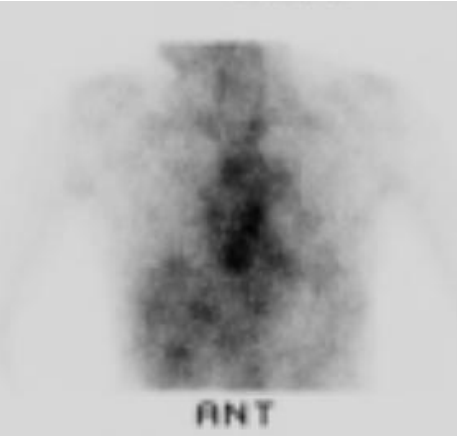
Answer: C – radiochemical impurity

Explanation: The image above shows thyroid uptake due to free pertechnetate rather than Tc-99m MAA. This may occur due to incomplete binding at production or breakdown following injection.

References:

1. Ponto, James. "The AAPM/RSNA Physics Tutorial for Residents. Radiopharmaceuticals." *Radiographics* 18:1385–1404, 1998.
2. Cherry, S.R., J.A. Sorenson, and M.E. Phelps. *Physics in Nuclear Medicine*, 4th ed. Philadelphia: Elsevier Saunders, 2012, p 59.

Q16: A Gallium scan is performed and a representative image is shown. The acquisition was fixed time, and the number of counts obtained were as expected. This could be caused by:



A. use of the wrong collimator
B. an incorrect window
C. a photomultiplier tube that needs retuning
D. an incorrect uniformity map

Answer: D – an incorrect uniformity map

Explanation: Many scintillation cameras require, as one of the correction maps, a uniformity map for each radionuclide used. For maps that have energies that are significantly different from Tc-99m, this map may require significant corrections. If the wrong map is used, as in this example, the pattern of PMTs is very evident in the image.

Reference:

1. Cherry, S.R., J.A. Sorenson, and M.E. Phelps. *Physics in Nuclear Medicine*, 4th ed. Philadelphia: Elsevier Saunders, 2012

Appendix A

2013 Committee Members

Kalpana M. Kanal, PhD, Chair
Jerry A. Thomas, MS, Vice Chair
Maxwell Amurao, PhD
Jon A. Anderson, PhD
Kimberly E. Applegate, MD
Gary J. Becker, MD
Richard H. Behrman, PhD
Margaret E. Blackwood, MS
Libby F. Brateman, PhD
Karen L. Brown, MHP
Jun Deng, PhD
Michael J. Dennis, PhD
Renee L. Dickinson, MS
Edward J. Goldschmidt, Jr., MS
Bennett S. Greenspan, MD
Philip H. Heintz, PhD
Shawn H. Heldebrandt, MS
Ping Hou, PhD
Zhengfeng Lu, PhD
Mary E. Moore, MS
Marleen M. Moore, MS
Venkataramanan Natarajan, PhD
John D. Newell, Jr., PhD
Frank N. Ranallo, PhD
Ronald Price, PhD
M. Gary Sayed, PhD
Ioannis Sechopoulos, PhD
William F. Sensakovic, PhD
Charles R. Wilson, PhD

Appendix B

History and General Comments About Intent of Curriculum

It has been suggested that radiologists embody three principal attributes: clinical acumen, mastery of technology, and dedication to safety and quality [William Hendee, Ph.D.]. A compelling argument exists that mastery of imaging technology is the linchpin to these attributes, and that one cannot master the technology without learning the principles and applications of the physics underlying the technology.

To ensure that every radiologist has the knowledge necessary to ensure the safe practice of radiology, especially in the daily application of radiation safety measures and in all other facets of patient safety during imaging, a more standardized approach to physics education at the resident level is necessary. The American Association of Physicists in Medicine (AAPM) held a Forum on Physics Education in January 2006 to address the issue. The RSNA sponsored a multi-organizational follow-up meeting in February 2007. The curriculum presented here is the result of that initiative.

This curriculum builds on basic principles of physics in order to facilitate an in-depth understanding of all imaging modalities and how they form high-quality and clinically significant images. Ultrasound and magnetic resonance imaging have not been shown to date to pose risks to patients, other than the obvious concern for patient safety in MRI caused by either internal or external ferromagnetic objects. However, the situation is different for modalities using ionizing radiation, such as radiography, fluoroscopy, nuclear medicine studies, and computed tomography, particularly the late-generation, multi-detector-row CT machines.

Ionizing radiation has been used for diagnostic imaging purposes in medicine for over a century. The benefits of such imaging exams almost certainly exceed the risks, no doubt further improving the lives of our patients. However, the dramatic growth of imaging use over the past few decades has also resulted in a significant increase in the population's cumulative exposure to ionizing radiation. Data extrapolated from the atomic bomb survivors in Japan and the nuclear catastrophe at Chernobyl predict that the incidence of imaging-related cancer in the exposed population may significantly increase in the coming years. This presumption makes it incumbent on radiologists to assume even further responsibility for the appropriate utilization of imaging studies, and then to ensure when imaging is used in a diagnostic setting that image quality is balanced by the concept of ALARA (as low as reasonably achievable) as it pertains to radiation dose.

All stakeholders in diagnostic imaging are encouraged to embrace the principles of imaging physics included in this curriculum, and to employ them in the best interests of patient safety by optimizing imaging to answer the clinical question posed while placing the patient at minimal risk.