CURRICULUM
UPDATED COPY
November 2024

Diagnostic Radiology Residents Physics Curriculum

Prepared by

Diagnostic Radiology Resident Physics Curriculum Working Group
AAPM Working Group of the Medical Physics Education of Physicians Committee

UPDATED – March 2024

Supported by: AAPM Education Council

Working Group members have contributed in the following manner:

Jie Zhang, PhD, Chair
Christina Brunnquell, PhD, Vice Chair

Module 1: Jie Zhang, PhD	Module 8: Trevor J Andrew, PhD Ping Hou, PhD	Module 15: Jie Zhang, PhD
Module 2: Yun Liang, PhD	Module 9: Adel A Mustafa, PhD Brandon J Russell, MS	Module 16: Megan E Lipford, PhD
Module 3: Jie Zhang, PhD	Module 10: Ashley E Rubinstein, PhD	Module 17: Trevor J Andrew, PhD
Module 4: Richard H Behrman, PhD	Module 11: Bennett S Greenspan, MD	Module 18: Willian F Sensakovic, PhD
Module 5: Ashley E Rubinstein, PhD	Module 12: Sameer Tipnis, PhD	Module 19: Karen L Brown, MHP
Module 6: Hamid Reza Khosravi, PhD	Module 13: Sameer Tipnis, PhD	Module 20: Willian F Sensakovic, PhD
Module 7: Christina Brunnquell, PhD	Module 14: Sameer Tipnis, PhD	

Format and Proofreading: Benjamin C. Musall, PhD, Ashley E. Rubinstein, PhD

Special Thanks: Kalpana M Kanal, PhD, Adrian A Sanchez, MD, PhD

TABLE OF CONTENTS

Preface

The physics curriculum for radiology residents, last updated in 2018, has been refreshed to integrate recent technological developments, emphasize practical clinical applications through the application of physics in radiology, provide a comprehensive review of modern physics in the field, and align with current radiological practices by synchronizing with the latest trends and methods in diagnostic radiology. The curriculum aims to outline the extensive scientific knowledge foundational to diagnostic radiology, enhancing a practicing radiologist's understanding of the strengths and limitations of their tools. It elaborates on the essential physics knowledge pertinent to medical imaging that a radiologist should master upon graduating from an accredited radiology residency program.

Compared to the 2018 curriculum, these updates represent a significant shift, adding new content areas and expanding existing modules. Notable updates include a dedicated module on artificial intelligence (AI) and informatics, advanced imaging techniques, and an expanded focus on radiation safety and protection. The Nuclear Medicine (NM) section has been reorganized into more detailed topics.

The curriculum is structured into 20 modules, each with three sections: learning objectives, curriculum content, and Q&A. The learning objectives outline fundamental knowledge and specific clinical applications, with examples of relevant clinical problems. The curriculum content presents the concepts each module addresses, with a priority score (3-Necessary, 2-Important, 1-If time allows) to guide educators on the importance of each topic. The Q&A section provides example questions to help residents and educators understand the type of questions that could be asked on the topic. For modality-based modules, the Q&A follows the format: Underlying Technology and Physical Principles, Effective Use, Artifacts, Safety, Quality Management, and Regulatory Issues, highlighted using parentheses.

This structure ensures a comprehensive understanding of imaging physics, preparing residents for the challenges of modern radiological practice. It is worth noting that this curriculum is designed for educators, not for residents, although residents are encouraged to use it.

MODULE 1: THE ATOM AND RADIOACTIVE DECAY

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

Fundamental Knowledge:

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

Clinical Applications and Problem Solving:

1. Explain and give examples of types of EM radiation used in imaging in radiology and nuclear medicine.
2. Understand why particulate radiation is not used for diagnostic imaging.

Curriculum:

1. The Atom and Radioactive Decay

1.1. Structure of the Atom [3]
- 1.1.1. Composition [3]
  - 1.1.1.1. Electrons [3]
  - 1.1.1.2. Nucleus [3]
- 1.1.2. Electronic Structure [2]
  - 1.1.2.1. Electron Orbits [2]
  - 1.1.2.2. Orbital Nomenclature [1]
  - 1.1.2.3. Binding Energy [3]
  - 1.1.2.4. Electron Transitions [3]
  - 1.1.2.5. Characteristic Radiation [3]
  - 1.1.2.6. Auger Electrons [1]
- 1.1.3. Nuclear Structure [3]
  - 1.1.3.1. Composition [3]
  - 1.1.3.2. Nuclear Force [1]
  - 1.1.3.3. Mass Defect [1]
  - 1.1.3.4. Binding Energy [3]

1.2. Electromagnetic (EM) Radiation [3]
- 1.2.1. The Photon [3]
  - 1.2.1.1. Electromagnetic Quanta [1]
  - 1.2.1.2. Origin of X-rays, Gamma Radiation, and Annihilation Radiation [3]
  - 1.2.1.3. Properties of Photons [3]
    - 1.2.1.3.1. Energy Mass Equivalence [2]

1.2.1.3.2. Speed [2]
1.2.1.3.3. Energy [3]
1.2.2. Electromagnetic Spectrum [3]
1.2.2.1. Electric and Magnetic Components [2]
1.2.2.2. Ionizing (e.g., X-rays, Gamma Rays) [3]
1.2.2.3. Non-Ionizing (e.g., RF, Visible Light) [3]
1.3. Particulate Radiation [3]
1.3.1. Electrons and Positrons [3]
1.3.2. Heavy Charged Particles [1]
1.3.2.1. Protons [1]
1.3.2.2. Alpha Particles [2]
1.3.3. Uncharged Particles [1]
1.3.3.1. Neutrons [1]
1.3.3.2. Neutrinos and Antineutrino [1]
1.4. Radionuclide Decay [3]
1.4.1. Nuclear Transformation [3]
1.4.1.1. N/Z Ratio and Nuclear Stability [3]
1.4.1.2. Beta (Negative Electron) Decay [3]
1.4.1.3. Positron (Positive Electron) Decay [3]
1.4.1.4. Electron Capture [3]
1.4.1.5. Isomeric Transition [3]
1.4.1.6. Alpha Decay [3]
1.4.1.7. Gamma and Internal Conversion [3]
1.4.1.8. Decay Modes of Commonly Used Radionuclides [3]
1.4.2. Radioactivity [3]
1.4.2.1. Definition of Radioactivity [3]
1.4.2.2. Units [3]
1.4.2.3. Decay Constant and Decay Rate [3]
1.4.2.4. Decay Equation [3]
1.4.2.5. Half-life (Physical, Biological, and Effective) [3]
1.4.3. Radioactive Equilibrium [3]
1.4.3.1. Transient and Secular [3]

Module Specific References

1. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
2. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.
3. Cherry, S. A., Sorenson, J. A., & Phelps, M. E. (2012). *Physics in Nuclear Medicine* (4th ed.). Saunders Elsevier.

Example Q&A:

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

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

Answer: D – Isotopes

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: C – Neutrons and protons

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

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

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q4. A proton is electrostatically repelled by:

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

Answer: E – Alphas

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: C – MRI

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: C – Alpha particles

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

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

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Cherry. (2012) *Physics in Nuclear Medicine*

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

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

Answer: A – Photons (>100 keV)

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q9. Which of the following radionuclide emissions is most useful for nuclear medicine imaging?

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

Answer: C – Gamma rays

Explanation: Particulate radiations such as electrons, alphas and protons have a limited range in human tissue. The particles will be absorbed within the body and will not reach an external imaging detector. Gamma rays are more penetrating and less likely to interact within the body, allowing a sufficient number of emissions to reach an external detector.

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: C – Atomic number

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: C – Characteristic x-ray

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

MODULE 2: INTERACTIONS OF IONIZING RADIATION WITH MATTER AND RADIATION UNITS

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

Fundamental Knowledge:

1. Describe various 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.
2. Identify how photons are attenuated within a material and the terms used to characterize the attenuation.
3. Understand the energy transfer from photons and charged particles to a medium (e.g., kerma).
4. Recognize that there are two different systems for units of measurement (e.g., SI and traditional) used to describe the concepts of dose-related quantities.
5. Describe the SI and traditional units for measuring radiation exposure (ionization resulting from radiation interactions in air) and radioactivity (radiation released by radioactive decay).

Clinical Applications and Problem Solving:

1. Identify which photon interactions are dominant for each imaging modality.
2. Understand the specific dependencies with regard to photon energy and atomic number of the absorber for each type of photon interactions and their associated clinical significance (e.g., kV, filter).
3. Understand how image quality and patient dose are affected by these interactions.
4. Understand which x-ray beam energies are to be used with intravenous iodine and oral barium contrast agents.
5. What is the purpose of adding filtration in x-ray imaging (e.g., copper, aluminum)?
6. How does half-value layer affect patient dose?
7. What makes a contrast agent radio-opaque?
8. What is the effect of backscatter on skin dose?
9. Discuss the appropriate use or applicability of radiation quantities in the health care applications of imaging, therapy, and safety.
10. Identify appropriate units for a given dose metric.
11. When is it appropriate to use effective dose vs. absorbed dose?

Curriculum:

2. Interactions of Ionizing Radiation with Matter and Radiation Units

2.1. Interactions of Ionizing Radiation with Matter [3]

- 2.1.1. Photon Interactions [3]
  - 2.1.1.1. Coherent Scattering [1]
  - 2.1.1.2. Photoelectric Effect [3]
  - 2.1.1.3. Compton Scattering [3]
  - 2.1.1.4. Pair Production [1]
- 2.1.2. Photon Attenuation [3]

- 2.1.2.1. Linear [3] and Mass [1] Attenuation
- 2.1.2.2. Mono-energetic and Poly-energetic Photon Spectra [3]
- 2.1.2.3. Half-value Layer (HVL) [3]
- 2.1.2.4. Effective Energy [3]
- 2.1.2.5. Beam Hardening [3]

2.1.3. Interactions in Materials of Clinical Interest [3]

- 2.1.3.1. Tissues [3]
- 2.1.3.2. Radiographic Contrast Agents [3]
- 2.1.3.3. Detector materials [2]
- 2.1.3.4. Shielding materials [2]

2.2. Radiation Units [3]

2.2.1. System of Units [3]

- 2.2.1.1. SI [3]
- 2.2.1.2. Prefixes: Nano- to Tera- [3]
- 2.2.1.3. Traditional [3]

2.2.2. Radioactivity [3]

- 2.2.2.1. Dosage [3]
- 2.2.2.2. SI – Becquerel (Bq) [3]
- 2.2.2.3. Traditional – Curie (Ci) [3]

2.2.3. Exposure [3]

- 2.2.3.1. Coulomb/kilogram [1]
- 2.2.3.2. Roentgen (R) [3]

2.2.4. Kinetic Energy Released in Matter (KERMA) [3]

- 2.2.4.1. Gray (Gy) [3]
- 2.2.4.2. Rad [2]

2.2.5. Absorbed Dose [3]

- 2.2.5.1. Gray (Gy) [3]
- 2.2.5.2. Rad [2]

2.2.6. Equivalent Dose [3]

- 2.2.6.1. Radiation Weighting Factors [3]
- 2.2.6.2. Sievert (Sv) [3]
- 2.2.6.3. Rem [2]

2.2.7. Effective Dose [3]

- 2.2.7.1. Tissue Weighting Factors [3]
- 2.2.7.2. Sievert (Sv) [3]
- 2.2.7.3. Rem [2]

Module Specific References

1. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
2. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.

Example Q&A:

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

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

Answer: B – Compton scattering

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: B – Photoelectric effect

Explanation: In bone, Compton scatter is the dominant photon interaction for photon energies > 45 keV. In radiography, the effective energy of the beam is between 1/3 to 1/2 kV. Because (80 kV) /2 = 40 kV, which is less than the 45 keV threshold, the photoelectric effect would dominate the interactions of the beam in bone.

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: C – kV

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: C – Photoelectric effect

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: C – Photoelectric effect

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q6. In interactions of x-ray and gamma ray radiation with matter, the occurrence of a sharp increase in photoelectric absorption is related to:

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

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

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q7. At 80 kV, assume the soft-tissue HVL is 4 cm. What is the approximate radiation dose to an embryo located 8 cm below the anterior surface, expressed as a percentage of the entrance skin dose?
A. 100%
B. 75%
C. 50%
D. 25%

Answer: D – 25%

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q8. Which of the following is the most penetrating of the radiations listed?

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

Answer: D – Photons from ^{18}F radioactive decay

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q9. The energy of each photon created when a positron interacts with an electron in an annihilation reaction is:

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

Answer: C. 511 keV

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q10. Which of the following is most damaging to tissue?

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

Answer: D – Protons (100 keV)

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q11. The unit for effective dose is:

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

Answer: D – mSv

Explanation: Sievert is the unit for effective dose.

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q12. 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: "Equivalent dose "─obtained by multiplying the absorbed dose by the radiation weighting factor (W_R), which is a function of the type and energy of the radiation─ is the defined by the International Commission on Radiological Protection.

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q13. A medical worker receives 30 mGy to an area of skin on the hand from alpha particles. The equivalent dose to this area of skin is:

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

Answer: D – 600 mSv

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q14. Which quantity provides a single index that relates to the overall stochastic risk (at diagnostic radiation dose levels) when multiple organs are irradiated?

A. Absorbed dose
B. Equivalent dose
C. Effective dose
D. Air kerma

Answer: C – Effective dose

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q15. Which statement is true regarding effective dose?

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

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

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q16. Convert a dosage of 20mCi ^{99m}Tc to MBq of ^{99m}Tc.

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

Answer: D – 740 MBq

Explanation: 1 mCi is equal to 37 MBq.

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

MODULE 3: X-RAY PRODUCTION

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

Fundamental Knowledge:

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

Clinical Applications and Problem Solving:

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

Curriculum:

3. X-ray Production
3.1. Interactions of Ionizing Radiation with Bremsstrahlung [2]
3.2. Characteristic Radiation [3]
3.3. Production of X-rays [3]
    3.3.1. X-ray Intensity and Dose [3]
    3.3.2. Electron Energy [2]
    3.3.3. Target Material [3]
    3.3.4. Filtration [3]
    3.3.5. Spectrum and Beam Quality [3]
3.4. X-ray Tube [3]
    3.4.1. Cathode [3]
        3.4.1.1. Filament [3]
        3.4.1.2. Filament Current and Tube Current [3]
    3.4.2. Anode [3]
        3.4.2.1. Target materials [3]
        3.4.2.2. Configurations (e.g., Angulation, Stationary vs. Rotating) [2]
        3.4.2.3. Line-focus Principle [2]
        3.4.2.4. Focal Spot [3]
        3.4.2.5. Heel Effect [3]
        3.4.2.6. Off-focus Radiation [1]
        3.4.2.7. Tube Heating and Cooling [2]
    3.4.3. Applications [3]

- 3.4.3.1. Mammography [3]
- 3.4.3.2. Radiography and Fluoroscopy (R&F) [3]
- 3.4.3.3. CT [3]
- 3.4.3.4. Interventional Fluoroscopy [3]
- 3.4.3.5. Mobile X-ray [3]
- 3.4.3.6. Dental [2]

3.5. Generators [2]
- 3.5.1. High-frequency [2]

3.6. Technique Factors [3]
- 3.6.1. Tube Voltage (kV) [3]
- 3.6.2. Tube Current (mA) [3]
- 3.6.3. Exposure Time [3]

3.7. X-ray Beam Modification [3]
- 3.7.1. Beam Filtration [3]
  - 3.7.1.1. Inherent [3]
  - 3.7.1.2. Added (Al, Cu, Mo, Rh, Ag, Other) [3]
  - 3.7.1.3. Minimum HVL [3]
  - 3.7.1.4. Compensation Filters [2]
- 3.7.2. Collimators [3]
  - 3.7.2.1. Field Size Limitation [1]
  - 3.7.2.2. Light Field and X-ray Field Alignment [1]
  - 3.7.2.3. Influence on Image Quality and Dose [3]

Module Specific References

1. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
2. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.

Example Q&A:

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

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

Answer: E – Patient dose is reduced

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: C – Geometric un-sharpness

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: A – Increased filtration

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

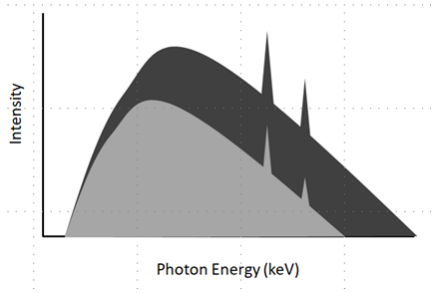
A. Image receptor farther from the focal spot
B. Large focal spot size
C. Smaller image size
D. No grid
E. X-ray tube with a smaller anode angle

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

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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



(Image courtesy of William F. Sensakovic, PhD, Mayo Clinic Arizona)

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

Answer: A – kV

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q6. Of all the x-rays in diagnostic imaging, what percentage does Bremsstrahlung x-rays production approximately account for?

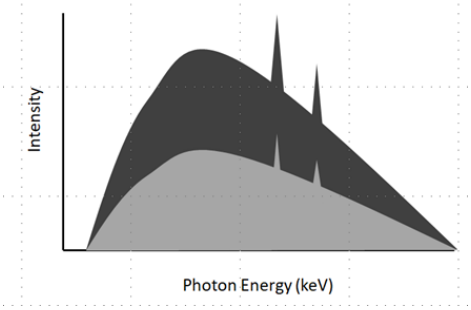
A. 85%
B. 30-85%
C. <30%

Answer: A – 85%

Explanation: Characteristic x-ray production depends on x-ray tube voltage. There are no characteristic x-rays produced at lower voltages, i.e., <69.5 kV. In this event, the x-ray production is 100% bremsstrahlung production.

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q7. In the figure below, two x-ray tube spectra are compared. What single parameter was changed between the acquisitions of the spectra?



(Image courtesy of William F. Sensakovic, PhD, Mayo Clinic Arizona)

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

Answer: D – mAs

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

MODULE 4: GENERAL RADIOGRAPHY

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

Fundamental Knowledge:

1. Describe the components and their function in a general radiographic imaging system.
2. List and describe the factors affecting radiographic image quality.
3. Describe the basic imaging requirements for specific body parts or views acquired in general radiography.
4. Define entrance skin air kerma and how it relates to patient dose.
5. Define Exposure Index and Deviation Index.

Clinical Applications and Problem Solving:

1. Describe how variations in system configuration affect patient dose and image quality.
2. Develop appropriate technique factors used in common radiographic procedures.
3. Analyze the radiation dose from a medical procedure and communicate the potential risks.
4. Determine when use of a grid is warranted or inappropriate.
5. Identify common artifacts seen in radiography and how they can be mitigated.
6. Describe differences in equipment and technique for imaging pediatric, adult, and bariatric patients.

Curriculum:

4. General Radiography

4.1. Underlying Technology and Physics Principles [3]

- 4.1.1. Geometry [3]
- 4.1.2. Inverse-Square Law [3]
- 4.1.3. Beam Divergence and Radiation Field Size (Field of View) [3]
- 4.1.4. System Geometry [3]
  - 4.1.4.1. Source-to-Image Distance (SID) [3]
  - 4.1.4.2. Source-to-Object Distance (SOD) [3]
  - 4.1.4.3. Object-to-Image Distance (OID) [3]
  - 4.1.4.4. Geometric Magnification [3]
- 4.1.5. Primary System Components [3]
  - 4.1.5.1. X-ray Tube and Generator [3]
  - 4.1.5.2. Filtration (Inherent, Added, and Compensation) [3]
  - 4.1.5.3. Collimator Assembly (Collimator and Light Field) [3]
  - 4.1.5.4. Anti-Scatter Grid and Bucky [3]
  - 4.1.5.5. Automatic Exposure Control (AEC) [3]
  - 4.1.5.6. Detector [3]
- 4.1.6. Radiographic Detectors [3]
  - 4.1.6.1. Detector Characteristics [2]
    - 4.1.6.1.1. Dynamic Range [2]
    - 4.1.6.1.2. Quantum Mottle, Electronic Noise, and Saturation [2]
    - 4.1.6.1.3. Detection Efficiency (Sensitivity) [1]
  - 4.1.6.2. Computed Radiography (CR, PSP-Photostimulable Phosphor) [1]

- 4.2.4.1. Readout Errors (e.g., Power Interruption, Electromagnetic Interference) [3]
- 4.2.4.2. Detector (e.g., Dead Pixels) [3]
- 4.2.4.3. Processing (e.g., Uniformity Correction) [3]
- 4.2.5. Dual-Energy X-ray Absorptiometry (DEXA)
- 4.2.5.1. Motion Artifacts [3]
- 4.2.5.2. Metallic and Contrast Agent Artifacts [3]
- 4.2.5.3. Soft Tissue Artifacts [3]

4.3. Effective Use [3]

- 4.3.1. Applications [3]
- 4.3.1.1. Head/Neck [3]
- 4.3.1.2. Chest [3]
- 4.3.1.3. Abdomen/Pelvis [3]
- 4.3.1.4. Spine [3]
- 4.3.1.5. Extremities [3]
- 4.3.1.6. Adult/Pediatric/Neonatal/Bariatric [3]
- 4.3.2. Acquisition Modes [3]
- 4.3.2.1. Stationary vs. Portable [3]
- 4.3.2.2. Table Bucky, Wall Stand, and Table Top [3]
- 4.3.2.3. Manual vs. AEC Technique [3]
- 4.3.3. Scatter and Scatter Reduction [3]
- 4.3.3.1. Scatter-to-Primary Ratio (Patient Size, Field Size, Acquisition Technique) [3]
- 4.3.3.2. Physical and virtual Anti-Scatter Grids [3]
- 4.3.3.2.1. Grid Ratio [3]
- 4.3.3.2.2. Focal Distance and SID [3]
- 4.3.3.2.3. Appropriate Selection [3]
- 4.3.3.2.4. Bucky Factor [3]
- 4.3.4. System Setup and Patient Positioning [3]
- 4.3.4.1. Collimation, Light Field, and Field of View [3]
- 4.3.4.2. AEC and Positioning - Effects on Dose and Image Quality [3]
- 4.3.4.3. Anti-Scatter Grids [3]
- 4.3.4.4. Technique Selection [3]

4.4. Safety, Quality Management, and Regulatory Issues [3]

- 4.4.1. Factors Affecting Patient Dose [3]
- 4.4.1.1. Patient Habitus [3]
- 4.4.1.2. Appropriate use of Patient Shielding [3]
- 4.4.1.3. Appropriate use of AEC [3]
- 4.4.2. Radiation Dose and Dose Indicators [3]
- 4.4.2.1. Entrance Skin Air Kerma [2]
- 4.4.2.2. Kerma-Area Product (KAP) [1]
- 4.4.2.3. Effective Dose [3]
- 4.4.2.4. Exposure Index (EI)/Deviation Index (DI) [2]
- 4.4.2.5. Typical Dose Values (Adult, Pediatric, and Fetal) [3]
- 4.4.3. Quality Assurance and Quality Control Program [1]
- 4.4.3.1. Repeat/Reject Analysis [1]
- 4.4.3.2. State/Federal Regulatory Requirements [1]
- 4.4.3.3. Oversight of Physicists and Technologists QA/QC Activities [1]

Module Specific References

1. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
2. Bushong, S. C. (2021). *Radiologic Science for Technologists: Physics, Biology, and Protection* (12th ed.). Elsevier.
3. Dance, D. R., et al. (2014). *Diagnostic Radiology Physics: A Handbook for Teachers and Students* (1st ed.). International Atomic Energy Agency.
4. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.
5. Nickoloff, E. L., et al. (2002). Pediatric high KV/filtered airway radiographs: comparison of CR and film-screen systems. *Pediatr Radiol*, *32*, 476-484,
6. Jones, A. K., et al. (2015). Ongoing quality control in digital radiography: report of AAPM Imaging Physics Committee Task Group 151. *Medical physics*, *42*(11), 6658-6670,
7. Wagner, L. K., Lester, R. G., & Saldana, L. R. (1997). *Exposure of the Pregnant Patient to Diagnostic Radiations: A Guide to Medical Management* (2nd ed.). Medical Physics Publishing.
8. Qutbi M, Soltanshahi M, Shiravand Y, Gorzi SK, Shafiei B, Asli IN. Technical and patient-related sources of error and artifacts in bone mineral densitometry using dual-energy X-ray absorptiometry: A pictorial review. Indian J Radiol Imaging. 2020 Jul-Sep;30(3):362-371. doi: 10.4103/ijri.IJRI_495_19. Epub 2020 Oct 15. PMID: 33273771; PMCID: PMC7694734.

Example Q&A:

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

A. Lateral hip
B. Lateral lumbar spine
C. AP wrist
D. AP abdomen

Answer: C – AP wrist

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Bushong. (2021) *Radiologic Science for Technologists: Physics, Biology, and Protection*

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

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

Answer: A – Decreasing tube voltage

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Bushong. (2021) *Radiologic Science for Technologists: Physics, Biology, and Protection*

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

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

Answer: B – Use a small focal spot

Explanation: Using a small focal spot reduces the size of the X-ray source, which minimizes the penumbra effect. A smaller focal spot results in sharper images with better resolution, as it decreases the spread of X-ray photons that contribute to the blur around the edges of structures in the image. This is crucial for obtaining clear and detailed radiographic images, especially when imaging fine anatomical details.

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Bushong. (2021) *Radiologic Science for Technologists: Physics, Biology, and Protection*

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

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

Answer: B – 5 mm

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Bushong. (2021) *Radiologic Science for Technologists: Physics, Biology, and Protection*

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

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

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

Explanation: The Bucky factor is the relative increase in x-ray intensity (or mAs) needed to maintain equal signal at the detector when a grid is used vs. when a grid is not used.

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Bushong. (2021) *Radiologic Science for Technologists: Physics, Biology, and Protection*

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

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

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

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Bushong. (2021) *Radiologic Science for Technologists: Physics, Biology, and Protection*

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

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

Answer: D – Use a smaller field of view

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Bushong. (2021) *Radiologic Science for Technologists: Physics, Biology, and Protection*

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

A. Indirect digital radiography
B. Direct digital radiography
C. Computed radiography
D. Film-screen radiography

Answer: C – Computed radiography

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Bushong. (2021) *Radiologic Science for Technologists: Physics, Biology, and Protection*

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

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

Answer: B – Detector element size

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Dance. (2014) *Diagnostic Radiology Physics: A Handbook for Teachers and Students*

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

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

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

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q11. (Effective Use) A radiograph of a neonate airway was obtained in the 1.5X geometric magnification mode. What acquisition parameter is the most critical to ensure optimal spatial resolution?

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

Answer: C – Small focal spot size

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q12. (Effective Use) What is the reason for excluding high-ratio grid use for mobile radiography?

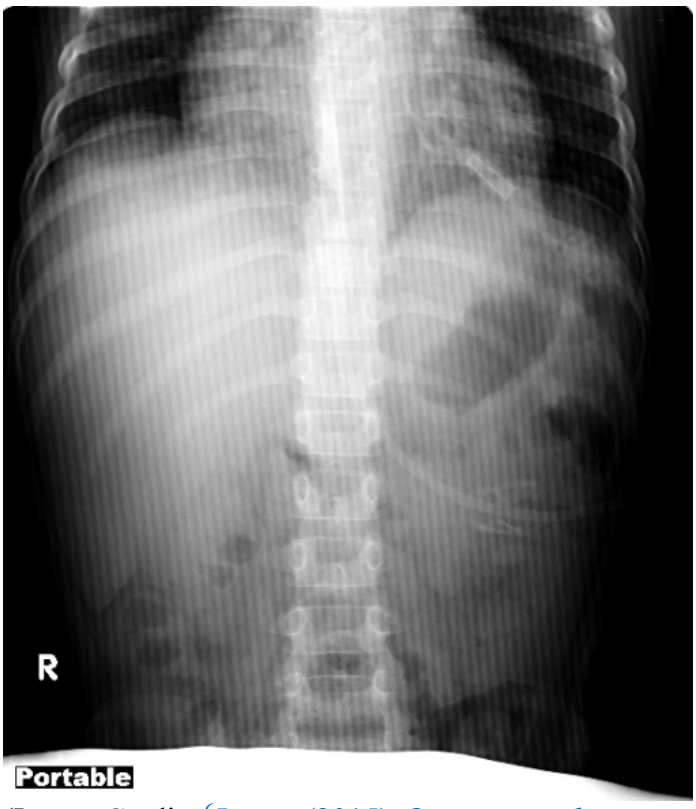
A. High-ratio grids have poorer scatter rejection than low-ratio grids
B. High-ratio grids are more difficult to align with the focal spot
C. High-ratio grids are more easily mis-positioned upside down as compared with low-ratio grids
D. High-ratio grids cannot be manufactured with short enough focal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

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

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [5]Nickoloff. (2002) *Pediatric high KV/filtered airway radiographs: comparison of CR and film-screen systems*

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



(Image Credit: [6]Jones. (2015) *Ongoing quality control in digital radiography: report of AAPM Imaging Physics Committee Task Group 151*)

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

Answer: B – Grid line interference

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

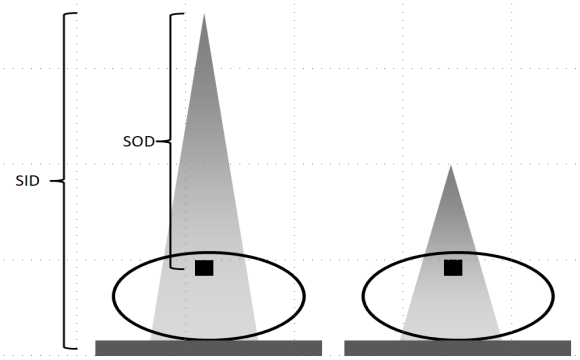
A. The anode side up and the cathode side down
B. The anode side down and the cathode side up
C. Either anode up or down, it makes no difference in chest image quality
D. Whether anode up or down depends on patient size
E. Whether anode up or down depends on radiologist's preference

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

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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



(Image courtesy of William F. Sensakovic, PhD, Mayo Clinic Arizona)

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

Answer: B – Decreased focal spot blurring

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

Abdomen	0.001 mSv
Extremities	0.7 mSv
Two-view mammogram – both breasts	0.02 mSv
Posteroanterior chest	0.01 mSv
Shoulder	0.4 mSv

Answer: Abdomen (0.7 mSv), Extremities (0.001 mSv), Two-view mammogram - both breasts (0.4), Posteroanterior Chest (0.02 mSv), Shoulder (0.01 mSv)

Explanation: These are the approximate effective doses for these procedures, averaged across patients.

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

A. Better
B. Equivalent
C. Worse

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

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: C – Reduce FOV with collimation

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [7]Wagner. (1997) *Exposure of the Pregnant Patient to Diagnostic Radiations: A Guide to Medical Management*

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

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

Answer: A – 75 kV, 20 mAs, 40" SID

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

MODULE 5 MAMMOGRAPHY

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

Fundamental Knowledge:

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

Clinical Applications and Problem Solving:

1. Describe how breast density and thickness variations may affect selection of the different targets and filters available in mammography systems.
2. Associate image quality changes with radiation dose changes (with and without magnification).
3. Understand the factors that influence detectability of microcalcifications and visualization of lesions in mammography.
4. Describe the source of common artifacts and methods to eliminate or reduce their appearance.
5. Understand the mechanism, advantages, and limitations of breast tomosynthesis and synthetic 2D images.
6. Explain computer-aided diagnosis/detection (CADx/CADe) and its impact in mammography.
7. Describe how a biopsy system can be used to localize and extract a sample from a suspected lesion.
8. Explain contrast-enhanced mammography and its advantages and limitations.

Curriculum:

5. Mammography

5.1. Underlying Technology and Physics Principles [3]

- 5.1.1. Acquisition System [3]
  - 5.1.1.1. Full-Field Digital Mammography [3]
  - 5.1.1.2. Biopsy Systems [3]
  - 5.1.1.3. Tomosynthesis [3]
  - 5.1.1.4. Contrast-Enhanced Mammography [2]
- 5.1.2. System Components [3]
  - 5.1.2.1. Target Materials [3]
  - 5.1.2.2. Filter Materials [3]
  - 5.1.2.3. Compression Paddles [3]
  - 5.1.2.4. Grid [3]
  - 5.1.2.5. Magnification Stand [3]

- 5.1.2.6. Automatic Exposure Control (AEC) [3]
- 5.1.2.7. Collimation [3]
- 5.1.2.8. Detectors [3]
- 5.1.3. Physics Principles [3]
  - 5.1.3.1. K-Edge Attenuation [3]
  - 5.1.3.2. X-Ray Spectrum [3]
  - 5.1.3.3. Target/Filter Combinations [3]
  - 5.1.3.4. Image Contrast and Attenuation of Breast Tissues and Lesions [3]
  - 5.1.3.5. Breast Compression [3]
  - 5.1.3.6. Stereotactic Visualization [2]
  - 5.1.3.7. Principles of Tomosynthesis [3]
  - 5.1.3.8. Principles of Contrast-Enhanced Mammography [2]
- 5.2. Effective Use [3]
  - 5.2.1. Clinical Importance [3]
    - 5.2.1.1. Benefits and Risks [3]
    - 5.2.1.2. Purpose of Screening and Diagnostic Mammography [3]
    - 5.2.1.3. Dedicated Equipment Requirements [3]
    - 5.2.1.4. Breast Anatomy [3]
  - 5.2.2. Image Acquisition [3]
    - 5.2.2.1. Source-to-Image, Source-to-Object, and Object-to-Detector Distances [3]
    - 5.2.2.2. Focal Spot Size [3]
    - 5.2.2.3. Collimation [2]
    - 5.2.2.4. Patient Positioning (e.g., Chest Wall Coverage) [3]
    - 5.2.2.5. Heel Effect [3]
    - 5.2.2.6. Grid vs. Air Gap [3]
    - 5.2.2.7. Magnification [3]
    - 5.2.2.8. 2D (Mammography) vs. 3D (Tomosynthesis) [3]
    - 5.2.2.9. Target/Filter and Acquisition Parameter Selection [3]
    - 5.2.2.10. Iodinated Contrast Enhancement [2]
  - 5.2.3. Image Processing [3]
    - 5.2.3.1. Raw, For-Processing and For-Presentation Images [2]
    - 5.2.3.2. Computed Aided Diagnosis/Detection (CADx/CADe) [2]
    - 5.2.3.3. Image Compression [2]
    - 5.2.3.4. Synthetic 2D Images [3]
  - 5.2.4. Workstations, PACS, and Display Requirements [3]
- 5.3. Image Characteristics and Artifacts [3]
  - 5.3.1. Machine-Related (e.g., Grid Lines Ghosting) [3]
  - 5.3.2. Patient-Related (e.g., Motion, Positioning) [3]
  - 5.3.3. Image Processing (e.g., Lossy Compression) [3]
- 5.4. Safety, Quality Management, and Regulatory Issues [3]
  - 5.4.1. Radiation Dose [3]
    - 5.4.1.1. Entrance Air KERMA [1]
    - 5.4.1.2. Average Glandular Dose (AGD) [3]
    - 5.4.1.3. Mammography Quality Standards Act (MQSA) Dose Limit [3]
    - 5.4.1.4. Effective dose [3]
    - 5.4.1.5. Pitfalls of Patient Shielding [3]

5.4.2. Factors Affecting Patient Dose [3]
5.4.2.1. Automatic Exposure Control (AEC), kV, Beam Quality, Target/Filter [3]
5.4.2.2. Breast Thickness and Composition [3]
5.4.2.3. 2D (Mammography) vs. 3D (Tomosynthesis) [3]
5.4.3. Quality Management [2]
5.4.4. Quality Control Program [3]
5.4.5. Regulatory Issues [3]
5.4.5.1. MQSA and Accreditation Bodies [3]
5.4.5.2. Responsibility of Radiologist, Technologist, and Physicist [3]
5.4.5.3. Patient and Occupational Protection [1]

Modality Specific References

1. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
2. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.
3. Carlton, R. R., Adler, A. M., & Balac, V. (2019). *Principles of Radiographic Imaging: An Art and a Science* (6th ed.). Cengage Learning.
4. Sensakovic, W. F., et al. (2021). Contrast-enhanced mammography: how does it work? *Radiographics*, *41*(3), 829-839,
5. ACR. (2024). *Mammography Accreditation*. https://www.acraccreditation.org/Modalities/Mammography
6. US-FDA. (2024). *Mammography Quality Standards Act and Program*. https://www.fda.gov/radiation-emitting-products/mammography-quality-standards-act-and-program
7. Bloomquist, A., et al. (2011). IAEA Human Health Series No. 17: Quality Assurance Programme for Digital Mammography. *Vienna: International Atomic Energy Agency*,
8. Ayyala, R. S., et al. (2008). Digital mammographic artifacts on full-field systems: what are they and how do I fix them? *Radiographics*, *28*(7), 1999-2008,
9. Geiser, W. R., Einstein, S. A., & Yang, W.-T. (2018). Artifacts in digital breast tomosynthesis. *American Journal of Roentgenology*, *211*(4), 926-932,
10. Jayadevan, R., et al. (2015). Optimizing digital mammographic image quality for full-field digital detectors: artifacts encountered during the QC process. *Radiographics*, *35*(7), 2080-2089,
11. Feng, S. S. J., & Sechopoulos, I. (2012). Clinical digital breast tomosynthesis system: dosimetric characterization. *Radiology*, *263*(1), 35-42,

Example Q&A:

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

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

Answer: A – 3

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: A – 0.3 mm

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

References:[2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*; [3]Carlton. (2019) *Principles of Radiographic Imaging: An Art and a Science*

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

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

Answer: C – High subject contrast

Explanation: At low kV the attenuation difference between different tissues is accentuated due to the increased photoelectric effect. This results in increased subject contrast. A second acquisition with higher kVs may be used for contrast enhanced mammography with dual energy subtraction imaging.

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*; [4]Sensakovic. (2021) *Contrast-enhanced mammography: how does it work?*

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

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

Answer: D – Image contrast

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*; [5]ACR. (2024) *Mammography Accreditation*; [6]US-FDA. (2024) *Mammography Quality Standards Act and Program*

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

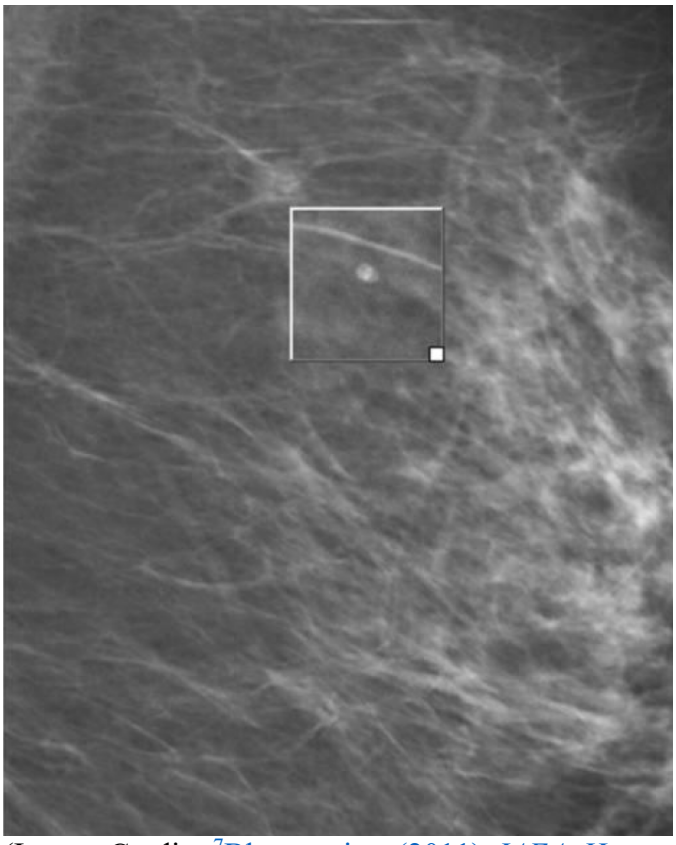
A. Achieves uniform exposure
B. Decreases the focal spot size
C. Minimizes motion artifact
D. Reduces acquisition time

Answer: A – Achieves uniform exposure

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q6. (Image Characteristics & Artifacts) What could be the cause of the degraded image quality seen in this mammogram?



(Image Credit: [7]Bloomquist. (2011) *IAEA Human Health Series No. 17: Quality Assurance Programme for Digital Mammography*)

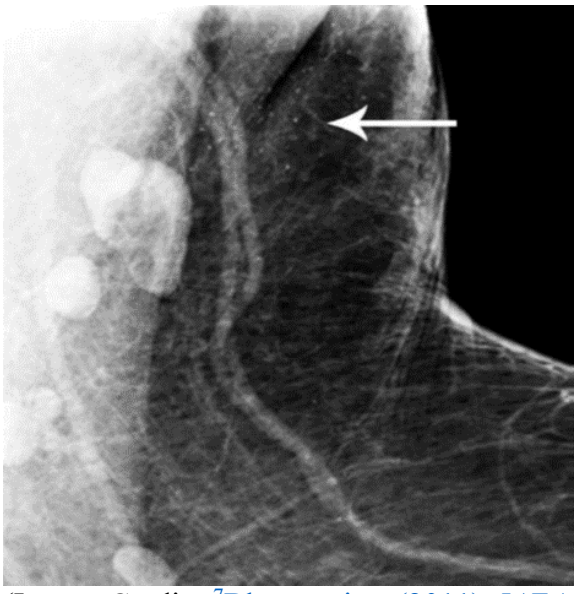
A. Low kV
B. Motion
C. Contrast
D. Noise

Answer: B – Motion

Explanation: Patient motion can lead to image blurring.

References:[7]Bloomquist. (2011) *IAEA Human Health Series No. 17: Quality Assurance Programme for Digital Mammography*; [8]Ayyala. (2008) *Digital mammographic artifacts on full-field systems: what are they and how do I fix them?*; [9]Geiser. (2018) *Artifacts in digital breast tomosynthesis*

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



(Image Credit: [7]Bloomquist. (2011) *IAEA Human Health Series No. 17: Quality Assurance Programme for Digital Mammography*)

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

Answer: C – Antiperspirant

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

References:[7]Bloomquist. (2011) *IAEA Human Health Series No. 17: Quality Assurance Programme for Digital Mammography*; [8]Ayyala. (2008) *Digital mammographic artifacts on full-field systems: what are they and how do I fix them?*

Q8. (Underlying Technology & Physical Principles) The pixel size in 2D digital mammography should be less than:

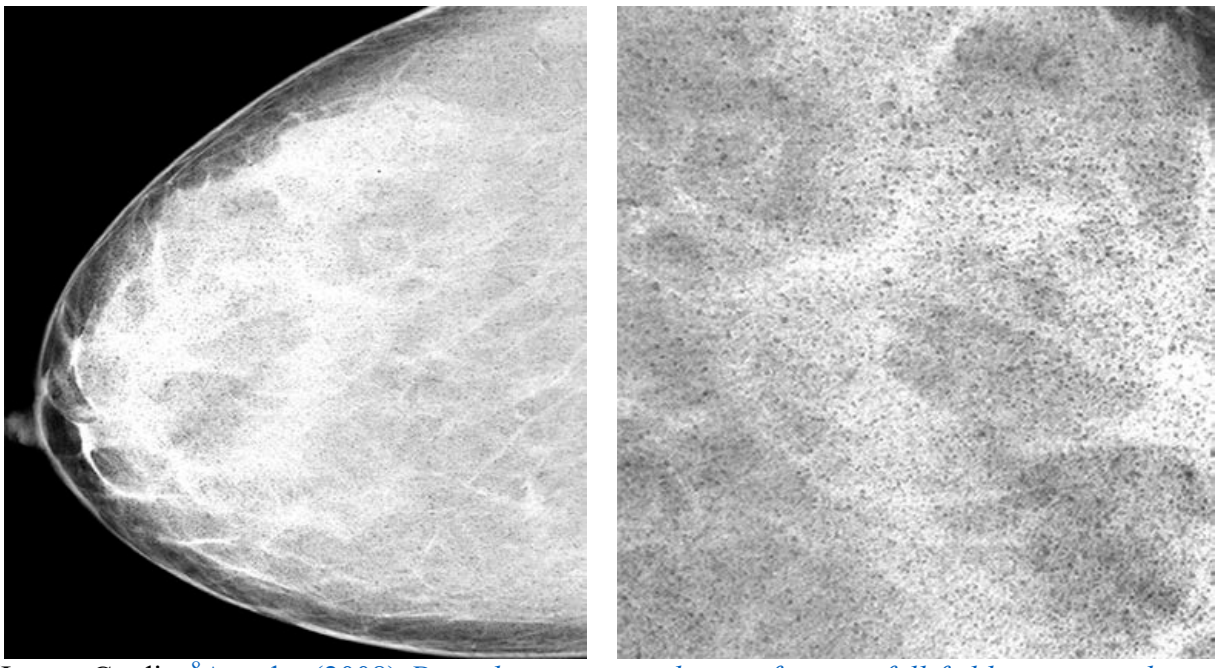
A. 50 µm
B. 70 µm
C. 100 µm
D. 140 µm

Answer: C – 100 µm

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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



(Image Credit: [8]Ayyala. (2008) *Digital mammographic artifacts on full-field systems: what are they and how do I fix them?*)

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

Answer: B – Underexposure

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

References:[8]Ayyala. (2008) *Digital mammographic artifacts on full-field systems: what are they and how do I fix them?*; [10]Jayadevan. (2015) *Optimizing digital mammographic image quality for full-field digital detectors: artifacts encountered during the QC process*

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

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

Answer: A – Comparable

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

References:[2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*; [5]ACR. (2024) *Mammography Accreditation*; [6]US-FDA. (2024) *Mammography Quality Standards Act and Program*; [11]Feng & Sechopoulos. (2012) *Clinical digital breast tomosynthesis system: dosimetric characterization*

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

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

Answer: C – W/Ag

Explanation: Large dense breasts require higher energies which are created by using Tungsten targets and Silver filters. Tungsten targets with aluminum give a higher energy as well, but are currently only used during tomosynthesis.

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

MODULE 6: GENERAL AND INTERVENTIONAL FLUOROSCOPIC IMAGING

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

Fundamental Knowledge:

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

Clinical Applications and Problem Solving:

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

Curriculum:

6. Fluoroscopy and Interventional Imaging

6.1. Underlying Technology and Physics Principles [3]

- 6.1.1. System Components [3]
  - 6.1.1.1. Tube [3]
  - 6.1.1.2. Filtration and Half-Value Layer [3]
  - 6.1.1.3. Collimation [3]
  - 6.1.1.4. Grids [3]
  - 6.1.1.5. Automatic Exposure Rate Control (AERC)/ Brightness Control (ABC) [3]
  - 6.1.1.6. Image Intensifier (II) [3]
    - 6.1.1.6.1. Brightness Gain [3]
    - 6.1.1.6.2. Minification (Geometric) Gain [3]

- 6.1.1.6.3. Flux Gain [3]
- 6.1.1.6.4. Field of View (FOV), Electronic Magnification [3]
- 6.1.1.7. Flat-panel [3]
- 6.1.1.7.1. Detector Technology [3]
- 6.1.1.7.2. Binning, Electronic Magnification [3]
- 6.1.1.8. Dose Monitoring Equipment [3]
- 6.1.2. Geometry [3]
- 6.1.2.1. Source-to-Image Receptor Distance (SID), Source-to-Object Distance (SOD), and Object-to-Image Receptor Distance (OID) [3]
- 6.1.2.2. Focal Spot Size [2]
- 6.1.2.3. Geometric Magnification [2]
- 6.1.2.4. System Configurations (e.g., C-arm, R&F, etc.) [3]

6.2. Image Characteristics and Artifacts [3]

- 6.2.1. Image Quality [3]
- 6.2.1.1. Image Contrast [3]
- 6.2.1.2. Spatial Resolution [3]
- 6.2.1.3. Temporal Resolution [3]
- 6.2.1.4. Noise [3]
- 6.2.1.5. Displays [1]
- 6.2.2. Artifacts [3]
- 6.2.2.1. Image Intensifier (II) Specific (e.g., Pincushion) [2]
- 6.2.2.2. Flat Panel Specific (e.g., Dead Pixels) [3]
- 6.2.2.3. Common Artifacts (e.g., Lag) [3]

6.3. Effective Use [3]

- 6.3.1. Operating Modes [3]
- 6.3.1.1. Continuous vs. Pulsed Fluoroscopy [3]
- 6.3.1.2. High-Level Control Mode Fluoroscopy (Boost) [3]
- 6.3.1.3. Variable Rate Pulsed Fluoroscopy [2]
- 6.3.1.4. Spot/Photospot Images [3]
- 6.3.1.5. Cine [3]
- 6.3.1.6. Digital Subtraction Angiography (DSA) [3]
- 6.3.1.7. Cone-beam CT Imaging (3D Rotational Angiography) [3]
- 6.3.1.8. Road Mapping [1]
- 6.3.2. Image Processing and Storage [3]
- 6.3.2.1. Temporal Recursive Filtering/Frame Averaging [3]
- 6.3.2.2. Last-Image Hold & Recording [3]
- 6.3.2.3. Real-time Image Processing [1]
- 6.3.2.4. Fluoroscopy Loop Recording [3]
- 6.3.3. Applications [3]
- 6.3.3.1. General Fluoroscopy [3]
- 6.3.3.2. Interventional Fluoroscopy [3]
- 6.3.3.3. Pediatric Procedures [3]
- 6.3.4. Protocol Optimization [3]
- 6.3.4.1. Acquisition Parameters (e.g., kV, Pulse Rate) [3]
- 6.3.4.2. Contrast Media [3]
- 6.3.4.3. Patient Positioning/Geometry [3]

6.3.4.4. Filtration [3]
6.3.4.5. Acquisition Mode [3]
6.3.4.6. Beam-On Time [3]
6.3.4.7. Image Processing [3]
6.3.4.8. Electronic Magnification [3]
6.3.4.9. Collimation [3]

6.4. Safety, Quality Management, and Regulatory Issues [3]
6.4.1. Quality Control [1]
6.4.2. Dose and Dosimetry [3]
6.4.3. Federal Regulations [3]
6.4.3.1. Dose Rate Limits [3]
6.4.3.2. Audible Alarms [3]
6.4.3.3. Minimum Source-to-Patient Distance [2]
6.4.4. Dose Metrics [3]
6.4.4.1. Peak Skin Dose [3]
6.4.4.2. Entrance Air Kerma [3]
6.4.4.3. KERMA-Area-Product (KAP) [3]
6.4.4.4. Cumulative Dose/Air KERMA & Interventional Reference Point (IRP)/manufacture-specified patient entrance reference point (PERP) [3]
6.4.4.5. Beam-On Time/Number of Acquisitions [3]
6.4.5. Patient Dose Tracking [3]
6.4.5.1. The Joint Commission Sentinel Event and Dose Tracking [3]
6.4.5.2. Patient Follow-up [3]
6.4.6. Typical Dose and Dose Rates [3]
6.4.7. Dose Dependence on Acquisition Parameters [3]
6.4.8. Operator and Staff Dose [3]
6.4.8.1. Typical Values [3]
6.4.8.2. Optimization (e.g., Position, Time, Distance, and Shielding) [3]

Module Specific References

1. Pooley, R. A., McKinney, J. M., & Miller, D. A. (2001). The AAPM/RSNA physics tutorial for residents: digital fluoroscopy. *Radiographics*, *21*(2), 521-534,
2. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
3. NCRP. (2010). *NCRP Report No. 168 - Radiation Dose Management for Fluoroscopically-guided Interventional Medical Procedures*. National Council on Radiation Protection and Measurements.
4. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.
5. Mettler Jr, F. A., Huda, W., Yoshizumi, T. T., & Mahesh, M. (2008). Effective doses in radiology and diagnostic nuclear medicine: a catalog. *Radiology*, *248*(1), 254-263,
6. Wang, J., & Blackburn, T. J. (2000). The AAPM/RSNA physics tutorial for residents: X-ray image intensifiers for fluoroscopy. *Radiographics*, *20*(5), 1471-1477,
7. NCRP. (2012). *NCRP Report No. 172 - Reference Levels and Achievable Doses in Medical and Dental Imaging: Recommendations for the United States*. National Council of Radiation Protection and Measurements.

8. Miller, D. L., et al. (2010). Clinical radiation management for fluoroscopically guided interventional procedures. *Radiology*, *257*(2), 321-332,
9. Schueler, B. A. (2000). The AAPM/RSNA physics tutorial for residents general overview of fluoroscopic imaging. *Radiographics*, *20*(4), 1115-1126,

Example Q&A:

Q1. (Effective Use) How should kV be set for the mask and post-contrast acquisitions during DSA?

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

Answer: C – Mask and post-contrast kV equal

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

References:[1]Pooley. (2001) *The AAPM/RSNA physics tutorial for residents: digital fluoroscopy*

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

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

Answer: A – Kerma-Area Product (KAP)

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]NCRP. (2010) *NCRP Report No. 168 - Radiation Dose Management for Fluoroscopically-guided Interventional Medical Procedures*

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

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

Answer: B – Maintain a constant noise or contrast-to-noise to the image receptor

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q4. (Underlying Technical and Physical Principles) Which dose metric reported in fluoroscopy may have units of Gy*cm^2?

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

Answer: C – Kerma-area product

Explanation: The units for kerma-area product are dose (e.g., mGy) times area (e.g., cm^2) so, mGy*cm^2.

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: D – Cine/Digital Run

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: A – High kV, low mA

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: C – 0.1%

Explanation: This is a common rule of thumb for fluoroscopy: scatter is 0.1% (1/1000) at 1m.

References: [2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q8. (Safety, Quality Management, and Regulatory Issues) Where should the image receptor be positioned in order to minimize patient dose?

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

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

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

References: [2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q9. (Safety, Quality Management, and Regulatory Issues) What is the FDA limit for exposure/KERMA rate in high level control mode (i.e., "boost" mode)?

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

Answer: D – 174 mGy/min (20 R/min)

Explanation: The FDA limits the maximum exposure/KERMA rate to 174 mGy/min (20 R/min) when using high dose rate exposure mode (AKA, boost mode) at a specified location.

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [5]Mettler Jr. (2008) *Effective doses in radiology and diagnostic nuclear medicine: a catalog*

Q10. (Safety, Quality Management, and Regulatory Issues) What is a typical effective dose from an upper gastrointestinal series?

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

Answer: C – 6 mSv

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [5]Mettler Jr. (2008) *Effective doses in radiology and diagnostic nuclear medicine: a catalog*

Q11. (Image Quality and Artifacts) Image intensifier (II) type image receptors are most susceptible to what artifact?

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

Answer: A – Pincushion Distortion

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q12. (Image Quality and Artifacts) Flat panel fluoroscopy systems are susceptible to which of the following?

A. Pincushion distortion
B. S-distortion
C. Vignetting
D. Dead pixels

Answer: D – Dead pixels

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q13. (Image Quality and Artifacts) Increasing what parameter increases the magnitude of S-distortion?

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

Answer: C – Field of view

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q14. (Image Quality and Artifacts) What artifact is exclusive to image-intensifier-based fluoroscopy and causes distortion of the image?

A. Ghosting
B. Non-uniformity
C. Dead detector element
D. Pincushion artifact

Answer: D - Pincushion artifact

Explanation: According to Wang et al., "Pincushion artifact is a geometric, nonlinear magnification across the image. The magnification difference at the periphery of the image results from the projection of the x-ray beam onto a curved input surface."

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [6]Wang & Blackburn. (2000) *The AAPM/RSNA physics tutorial for residents: X-ray image intensifiers for fluoroscopy*

Q15. (Safety, Quality Management, and Regulatory Issues) At a fluoroscopically guided interventional (FGI) facility, a review of cases shows that the kerma-area product regularly exceeds national reference levels. What is the most appropriate next step?

A. Verify equipment function and protocol
B. Notify the patients of possible skin effects
C. Review personnel dosimetry records
D. Discontinue the procedure

Answer: A – Verify equipment function and protocol

Explanation: NCRP Report No. 172 recommends reference levels for various procedures across imaging modalities. If a review of cases for a particular exam shows that the reference levels are routinely exceeded, the first recommended step is to investigate the fluoroscopic equipment, protocols, and operator performance.

References:[7]NCRP. (2012) *NCRP Report No. 172 - Reference Levels and Achievable Doses in Medical and Dental Imaging: Recommendations for the United States*

Q16. (Safety, Quality Management, and Regulatory Issues) In interventional fluoroscopy, what is the basis for defining the interventional reference point (IRP) at a distance of 15 cm from isocenter toward the x-ray tube?

A. It is an arbitrary choice of distance from the x-ray source
B. It approximates where the x-ray beam enters the patient's skin
C. It is where the FDA specifies a limit on the maximum air-kerma rate
D. It is a point that can never be inside the patient's anatomy

Answer: B – It approximates where the x-ray beam enters the patient's skin

Explanation: The interventional reference point (IRP) approximates the location where the x-ray beam enters the skin of the patient. With an interventional c-arm, the center of a patient (in the anteroposterior direction) is typically positioned at or near the isocenter. Given a standard 30-cm-thick patient, the x-ray beam skin entrance location would be located at 15 cm from isocenter toward the x-ray tube.

References:[8]Miller. (2010) *Clinical radiation management for fluoroscopically guided interventional procedures*

Q17. (Effective Use) In fluoroscopy, how does the dose rate associated with digital subtraction angiography (DSA) compare with that of normal fluoroscopic imaging mode?

A. DSA dose rate is much lower than normal fluoroscopy
B. DSA dose rate is about the same as normal fluoroscopy
C. DSA dose rate is much higher than normal fluoroscopy

Answer: C – DSA dose rate is much higher than normal fluoroscopy

Explanation: The dose rate for acquisition modes of imaging in fluoroscopy is considerably higher than those for both "normal" and "high-level control" modes of fluoroscopy.

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*

Q18. (Underlying Technical and Physical Principles) How does the exposure rate of an image-intensified fluoroscopic system using automatic brightness control change from a 10-cm to 15-cm magnification mode?

A. Stays the same
B. Decreases
C. Increases

Answer: B – Decreases

Explanation: On systems using automatic brightness control, the exposure rate will decrease with an increase in the minification gain.

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*

Q19. (Underlying Technical and Physical Principles) What is the purpose of added filtration in fluoroscopic imaging?

A. To reduce the temporal resolution of pulsed acquisitions
B. To remove low-energy photons from the beam
C. To remove high-energy photons from the beam
D. To improve the temporal resolution of pulsed acquisitions

Answer: B – To remove low-energy photons from the beam

Explanation: Filtration is added to the beam to preferentially remove low-energy photons from the beam to reduce patient skin dose.

References:[9]Schueler. (2000) *The AAPM/RSNA physics tutorial for residents general overview of fluoroscopic imaging*

Q20. (Effective Use) What is the most appropriate precaution to reduce peak skin dose during fluoroscopically guided interventional procedures?

A. Maximize the distance between the patient and the image receptor
B. Vary the table height throughout the exam
C. Vary the gantry angulation throughout the exam
D. Maximize the collimated field size

Answer: C – Vary the gantry angulation throughout the exam

Explanation: Using gantry angulation will help spread the dose over the skin to different areas, as long as caution is taken to avoid overlapping fields. Wide collimation increases the possibility of overlap and exposes a larger area of the skin to radiation. Adjusting the table height throughout the exam is often impractical, and positioning the patient far from the image receptor reduces skin distance to the tube, increasing patient dose.

References:[3]NCRP. (2010) *NCRP Report No. 168 - Radiation Dose Management for Fluoroscopically-guided Interventional Medical Procedures*

Q21. (Effective Use) For a fluoroscopically guided interventional procedure, what is the purpose of a defined substantial radiation dose level (SRDL)?

A. To trigger additional dose management
B. To monitor interventional team exposure
C. To identify a safe radiation level
D. To identify high risk for stochastic effects

Answer: A – To trigger additional dose management

Explanation: According to NCRP Report No. 168, the purpose of setting substantial radiation dose levels (SRDLs) is to identify cases with a high potential for deterministic skin effects and to trigger additional dose management, such as patient follow-up.

References:[3]NCRP. (2010) *NCRP Report No. 168 - Radiation Dose Management for Fluoroscopically-guided Interventional Medical Procedures*

MODULE 7: COMPUTED TOMOGRAPHY (CT)

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

Fundamental Knowledge:

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

Clinical Applications and Problem Solving:

1. Describe how tube current modulation and tube voltage selection affects patient dose and image quality.
2. Describe the sources of common artifacts and methods to eliminate or reduce their appearance.
3. Describe how CT protocols could be optimized for different age/size patients and clinical indications (image quality/dose tradeoff).
4. Discuss the limitations of CT dose metrics in estimating patient dose.

Curriculum:

7. Computed Tomography (CT)

7.1. Underlying Technology and Physics Principles [3]

- 7.1.1. System Components [3]
  - 7.1.1.1. Gantry/Beam Geometry [3]
  - 7.1.1.2. Tube (Fixed and Flying Focal Spot) [2]
  - 7.1.1.3. Beam Filtration and Shaping (Bow-Tie) Filters [3]
  - 7.1.1.4. Collimation [3]
  - 7.1.1.5. Detector Types and Configuration [3]
- 7.1.2. System Types [3]
  - 7.1.2.1. Multi-Detector Channel (Up to ~8cm Coverage) [3]
  - 7.1.2.2. Dual Source [3]
  - 7.1.2.3. Wide Detector (≥12 cm coverage) [2]
- 7.1.3. Acquisition Modes [3]
  - 7.1.3.1. Localizer Radiograph (Scout, Surview, Topogram, Scanogram, etc.) [3]
  - 7.1.3.2. Axial/Sequential [3]
  - 7.1.3.3. Cine Mode
  - 7.1.3.4. Helical/Spiral [3]
  - 7.1.3.5. Cardiac/Respiratory Gated [2]

7.1.3.6. Dynamic Scan Mode (Shuttle, Jog, Adaptive 4D, etc.) [2]
7.1.3.7. CT Fluoroscopy [1]
7.1.3.8. Dual Energy Modes & Hardware (kV Switching, Dual-layer Detector, Dual Source, etc.) [3]
7.1.4. Image Acquisition Parameters [3]
7.1.4.1. Tube Voltage (kV) [3]
7.1.4.2. Tube Current (mA) [3]
7.1.4.3. Rotation Time [3]
7.1.4.4. Tube Current-Time Product (mAs) and Effective mAs [3]
7.1.4.5. Pitch [3]
7.1.4.6. Detector Configuration and Beam Width [3]
7.1.4.7. Scan Field of View [3]
7.1.4.8. Image Quality Parameters (Noise Index, Reference mAs, etc.) [3]
7.1.5. Image Reconstruction [3]
7.1.5.1. Sinogram [2]
7.1.5.2. Filtered-Back Projection [3]
7.1.5.3. Statistical and Model-Based Iterative Reconstruction [3]
7.1.5.4. AI-/DL-based Reconstruction [2]
7.1.5.5. Reconstruction Filters/Convolution Kernels [3]
7.1.5.6. Helical Reconstruction and Interpolation [1]
7.1.5.7. CT Number/Hounsfield Unit [3]
7.1.5.8. Reconstruction Thickness and Interval [3]
7.1.5.9. Reconstruction/Display Field of View [3]
7.1.5.10. Dual Energy Reconstructions (Virtual Non-contrast, Virtual Monoenergetic, etc.) [3]
7.2. Effective Use [3]
7.2.1. Clinical Applications and Protocols [3]
7.2.1.1. Automatic Tube Current Modulation [3]
7.2.1.2. Automatic kV Selection [3]
7.2.1.3. Patient Size/Age Technique Adjustments [3]
7.2.1.4. Single vs. Multi-Phase Exams [3]
7.2.1.5. Perfusion CT [2]
7.2.1.6. Cardiac CT [3]
7.2.1.7. CT Angiography [2]
7.2.1.8. Dual Energy CT [2]
7.2.1.9. Bolus Dynamics [2]
7.2.2. Typical Tissue Hounsfield Units and Quantitative Use [3]
7.2.3. Factors Affecting Image Quality and Dose [3]
7.2.3.1. Image Acquisition Parameters [3]
7.2.3.1.1. Respiratory/Cardiac Gating [2]
7.2.3.1.2. Dual Source/Dual Energy [2]
7.2.3.1.3. Number of Phases (e.g., Pre- and Post-contrast) [2]
7.2.3.2. Image Reconstruction Parameters [3]
7.2.3.3. Patient Size and Centering [3]
7.2.3.4. Patient Dose Reduction [3]
7.2.3.4.1. Organ Dose Modulation [2]

7.2.3.4.2. Patient Shielding [1]
7.3. Image Characteristics and Artifacts [3]
7.3.1. Spatial, Contrast, and Temporal Resolution [3]
7.3.2. Signal-to-Noise Ratio (SNR) and Contrast-to-Noise Ratio (CNR) [2]
7.3.2.1. Limitations in Iterative and AI/DL-based reconstruction [1]
7.3.3. Artifacts and Mitigation [3]
7.3.3.1. Patient-Related (Motion, Metal, etc.) [3]
7.3.3.2. Scanner-Related (Ring Artifact, Undersampling, etc.) [3]
7.3.4. Image Processing and Image Display [2]
7.3.4.1. Window and Level Control [3]
7.3.4.2. Multi-planar Reconstruction (MPR) [3]
7.3.4.3. Maximum Intensity Projection (MIP) [2]
7.3.4.4. 3D Volume and Surface Rendering [1]
7.3.4.5. Overlays (Dual Energy and Perfusion) [1]
7.3.4.6. Virtual Fly Through [1]
7.4. Safety, Quality Management, and Regulatory Issues [3]
7.4.1. Dose Descriptors [3]
7.4.1.1. Computed Tomography Dose Indices (CTDI, $CTDI_{vol}$, etc.) [3]
7.4.1.2. Dose-Length Product (DLP) [3]
7.4.1.3. Organ Dose [1]
7.4.1.4. Fetal Dose [3]
7.4.1.5. Size-Specific Dose Estimate (SSDE) [2]
7.4.1.6. Effective Dose and k-factors [3]
7.4.2. Typical Dose Values [3]
7.4.3. Adult, Pediatric, and Bariatric Protocol Review and Optimization [3]
7.4.3.1. Image Gently [2]
7.4.3.2. Image Wisely [2]
7.4.4. Quality Control/Assurance [2]
7.4.5. Dose Monitoring and Reporting [2]
7.4.6. Accreditation and Regulatory Requirements [2]
7.4.6.1. American College of Radiology (ACR) [2]
7.4.6.2. The Joint Commission (TJC) [2]

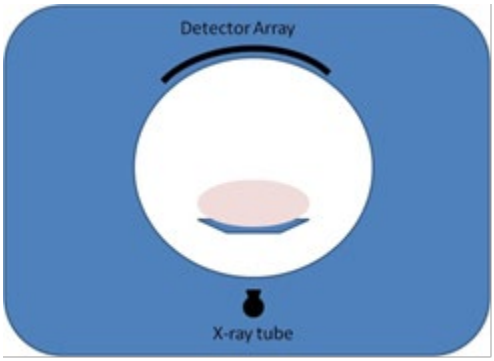
Module Specific References

1. McNitt-Gray, M., & DABR, F. (2011). Tube current modulation approaches: overview, practical issues and potential pitfalls. *AAPM 2011 Summit on CT Dose, Denver*,
2. Seeram, E. (2022). *Computed Tomography-E-Book: Physical Principles, Patient Care, Clinical Applications, and Quality Control* (4th ed.). Elsevier Health Sciences.
3. ACR. (2024). *CT Accreditation Program Requirements*. https://accreditationsupport.acr.org/support/solutions/articles/11000061279-complete-accreditation-information-ct
4. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
5. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.

6. Kalender, W. A. (2011). *Computed tomography: fundamentals, system technology, image quality, applications* (3rd ed.). John Wiley & Sons.
7. Lee, M.-J., et al. (2007). Overcoming artifacts from metallic orthopedic implants at high-field-strength MR imaging and multi-detector CT. *Radiographics*, *27*(3), 791-803,
8. Szczykutowicz, T. (2020). *The CT handbook: optimizing protocols for today's feature-rich scanners* (1st ed.). Medical Physics Publishing.

Example Q&A:

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



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

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

Answer: C – Quantum noise

Explanation: With the tube stationary under the patient and the patient positioned below isocenter for the acquisition of the scout view, the patient will appear larger than actual size, and a higher tube current will be used. Higher tube current will result in less quantum noise and, therefore, increased low-contrast visibility. Patient dose will increase proportionally with increased tube current. Spatial and temporal resolution will not be affected by a change in tube current.

References:[1]McNitt-Gray & DABR. (2011) *Tube current modulation approaches: overview, practical issues and potential pitfalls*; [2]Seeram. (2022) *Computed Tomography-E-Book: Physical Principles, Patient Care, Clinical Applications, and Quality Control*

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

75 mGy	Adult Body
35 mGy	Adult Head
25 mGy	Pediatric Body (40-50 lbs)
15 mGy	Pediatric Head (1 yr)

Answer: 75 mGy for Adult Head, 35 mGy for Pediatric Head, 25 mGy for Adult Body, 15 mGy for Pediatric Body (40-50 lbs)

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

References:[3]ACR. (2024) *CT Accreditation Program Requirements*

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

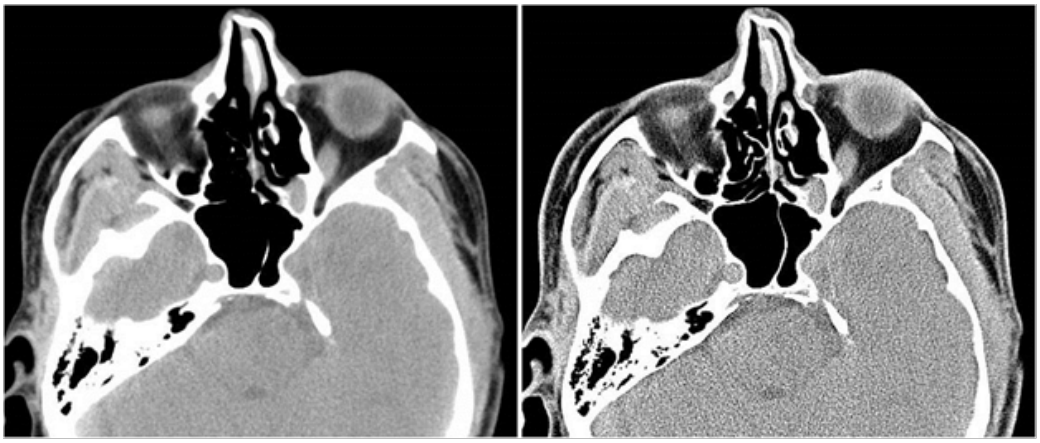
A. Tube current
B. Rotation time
C. Slice thickness
D. Increase kV

Answer: C –Slice thickness

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

References:[2]Seeram. (2022) *Computed Tomography-E-Book: Physical Principles, Patient Care, Clinical Applications, and Quality Control*; [4]Bushberg. (2021) *The Essential Physics of Medical Imaging*

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



(Image courtesy of William F. Sensakovic, PhD, Mayo Clinic Arizona)

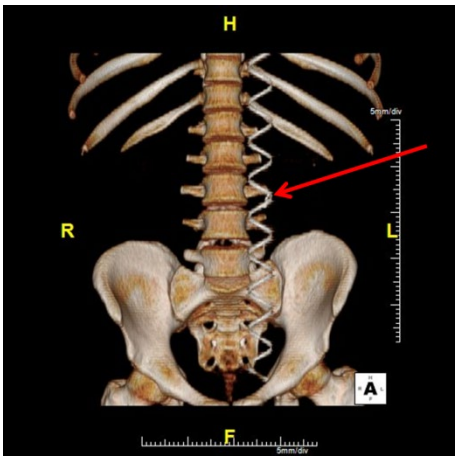
A. Beam energy
B. Tube current
C. Gantry angle
D. Convolution kernel

Answer: D – Convolution kernel

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

References:[4]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [5]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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



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

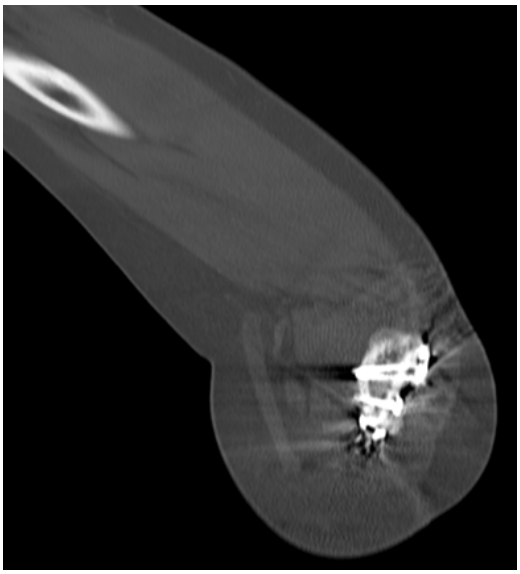
A. Patient motion
B. Beam hardening
C. Poor detector calibration
D. Partial volume averaging

Answer: C. Poor detector calibration

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

References:[2]Seeram. (2022) *Computed Tomography-E-Book: Physical Principles, Patient Care, Clinical Applications, and Quality Control*; [4]Bushberg. (2021) *The Essential Physics of Medical Imaging*

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



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

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

Answer: D – Increase tube voltage

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

References:[6]Kalender. (2011) *Computed tomography: fundamentals, system technology, image quality, applications*; [7]Lee. (2007) *Overcoming artifacts from metallic orthopedic implants at high-field-strength MR imaging and multi-detector CT*; [8]Szczykutowicz. (2020) *The CT handbook: optimizing protocols for today's feature-rich scanners*

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

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

Answer: D – kV

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

References:[4]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [5]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

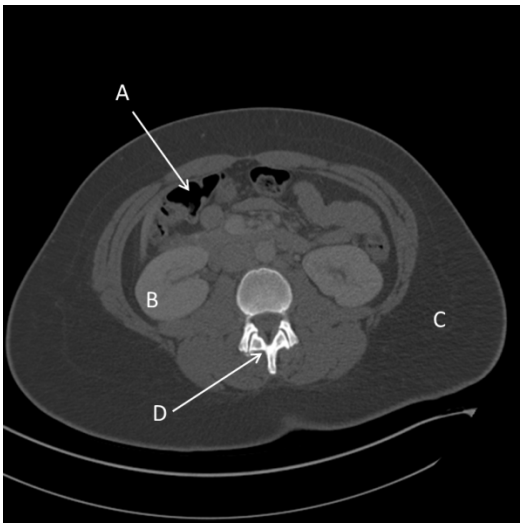
A. Translate-rotate
B. Rotate-rotate
C. Rotate-stationary
D. Stationary-translate

Answer: B – Rotate-rotate

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

References:[2]Seeram. (2022) *Computed Tomography-E-Book: Physical Principles, Patient Care, Clinical Applications, and Quality Control*; [5]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q9. (Effective Use) Match each labeled healthy tissue from the image below to one of the typical CT number (Hounsfield Unit) from this list: *-1000 HU, -120 HU, 140 HU, 800 HU*



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

Answer: -1000 HU for air (A), -120 HU for fat (C), 140 HU for the kidney (B), and 800 HU for bone (D)

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

References:[2]Seeram. (2022) *Computed Tomography-E-Book: Physical Principles, Patient Care, Clinical Applications, and Quality Control*; [4]Bushberg. (2021) *The Essential Physics of Medical Imaging*

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

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

Answer: D – Brain perfusion

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

References:[4]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [5]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: A – Daily

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

References:[3]ACR. (2024) *CT Accreditation Program Requirements*

Q12. (Image Characteristics and Artifacts) Which of the following factors influences in-plane spatial resolution?

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

Answer: D – Display field of view

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

References:[4]Bushberg. (2021) *The Essential Physics of Medical Imaging*

MODULE 8: MAGNETIC RESONANCE IMAGING (MRI)

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

Fundamental Knowledge:

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

Clinical Applications and Problem Solving:

1. Identify the most appropriate pulse sequences for a specific diagnostic task.
2. Describe the risks (e.g. acoustic, B0 limits) when MR imaging is used on a pregnant patient.
3. Discuss clinical situations in which MRI procedures are contra-indicated (e.g. implants).
4. Determine the source of common artifacts and describe methods to mitigate their appearance.
5. Discuss how different field strength systems change the acquisition parameters and image quality in MRI
6. Discuss how MR parameters affect biosafety.

Curriculum:

8. Magnetic Resonance Imaging

8.1. Underlying Technology and Physics Principles [3]

- 8.1.1. Magnetism and Magnetic Fields [3]
  - 8.1.1.1. Magnetic Susceptibility (Diamagnetic, Paramagnetic, Ferromagnetic) [3]
- 8.1.2. Static Magnetic Fields (B) [3]
  - 8.1.2.1. Magnetic Dipole and Magnetic Moment [1]
  - 8.1.2.2. Nuclear Magnetism (Protons and Biologically Relevant Nuclei) [2]
- 8.1.3. Magnetic Moment Interaction with an External Field (B0) [3]
  - 8.1.3.1. Precession Frequency [3]

8.4.2.6.3. Magnetic and RF Field Shielding [1]
8.4.2.7. ACR/TJC Accreditation and Quality Improvement [1]
8.4.2.7.1. MR Quality Assurance Committee [1]

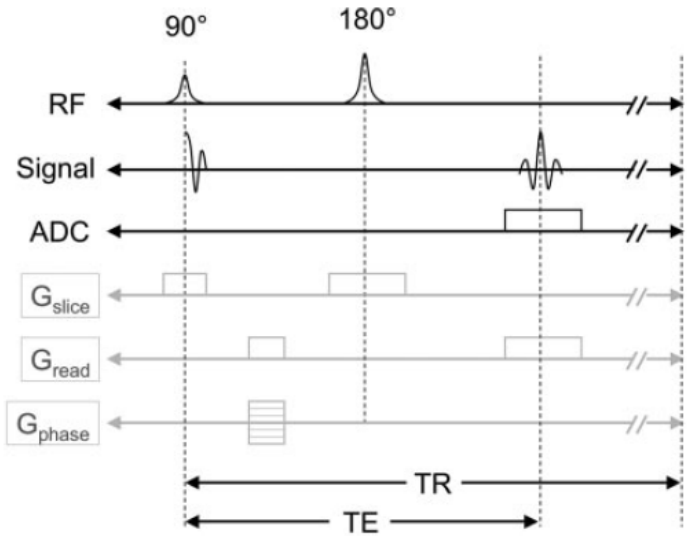
Module Specific References

1. Pooley, R. A. (2005). Fundamental physics of MR imaging. *Radiographics*, *25*(4), 1087-1099,
2. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
3. Runge, V. M., & Heverhagen, J. T. (2022). *The Physics of Clinical MR Taught Through Images* (5th ed.). Springer Nature.
4. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.
5. Qureshi, M., Kaleem, M., & Omer, H. (2017). Journey through k-space: an interactive educational tool. *Biomedical Research*, *28*(4), 7,
6. Hashemi, R. H., Bradley, W. G., & Lisanti, C. J. (2017). *MRI: The Basics* (4th ed.). Lippincott Williams & Wilkins.
7. McRobbie, D. W., Moore, E. A., Graves, M. J., & Prince, M. R. (2017). *MRI from Picture to Proton* (3rd ed.). Cambridge university press.
8. Kanal, E., et al. (2007). ACR guidance document for safe MR practices: 2007. *American Journal of Roentgenology*, *188*(6), 1447-1474,
9. ACR Committee on MR Safety, et al. (2020). ACR guidance document on MR safe practices: Updates and critical information 2019. *Journal of Magnetic Resonance Imaging*, *51*(2), 331-338,
10. Zhuo, J., & Gullapalli, R. P. (2006). MR artifacts, safety, and quality control. *Radiographics*, *26*(1), 275-297,
11. McRobbie, D. W. (2020). *Essentials of MRI safety* (1st ed.). John Wiley & Sons.
12. Expert Panel on MR Safety, et al. (2013). ACR guidance document on MR safe practices: 2013. *Journal of Magnetic Resonance Imaging*, *37*(3), 501-530,
13. Hardy, P. T., & Weil, K. M. (2010). A review of thermal MR injuries. *Radiologic technology*, *81*(6),
14. Dixon, W. T. (1984). Simple proton spectroscopic imaging. *Radiology*, *153*(1), 189-194,
15. Bitar, R., et al. (2006). MR pulse sequences: what every radiologist wants to know but is afraid to ask. *Radiographics*, *26*(2), 513-537,
16. Graves, M. J., & Mitchell, D. G. (2013). Body MRI artifacts in clinical practice: a physicist's and radiologist's perspective. *Journal of Magnetic Resonance Imaging*, *38*(2), 269-287,
17. Arena, L., Morehouse, H. T., & Safir, J. (1995). MR imaging artifacts that simulate disease: how to recognize and eliminate them. *Radiographics*, *15*(6), 1373-1394,
18. Elster, A. D. (2024). *Questions and Answers in MRI*. mriquestions.com
19. Edelman, R. R., & Hesselink, J. R. (2005). *Clinical Magnetic Resonance Imaging* (3rd ed.). WB Saunders Company.
20. ACR. (2020). *ACR Manual on MR Safety*. American College of Radiology. https://www.acr.org/-/media/ACR/Files/Radiology-Safety/MR-Safety/Manual-on-MR-Safety.pdf

21. Allison, J., & Yanasak, N. (2015). What MRI sequences produce the highest specific absorption rate (SAR), and is there something we should be doing to reduce the SAR during standard examinations? *American Journal of Roentgenology*, *205*(2), W140-W140,

Example Q&A:

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



(Image Credit: [1]Pooley. (2005) *Fundamental physics of MR imaging*)

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

Answer: D – Spin echo (SE) sequence

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Runge & Heverhagen. (2022) *The Physics of Clinical MR Taught Through Images*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

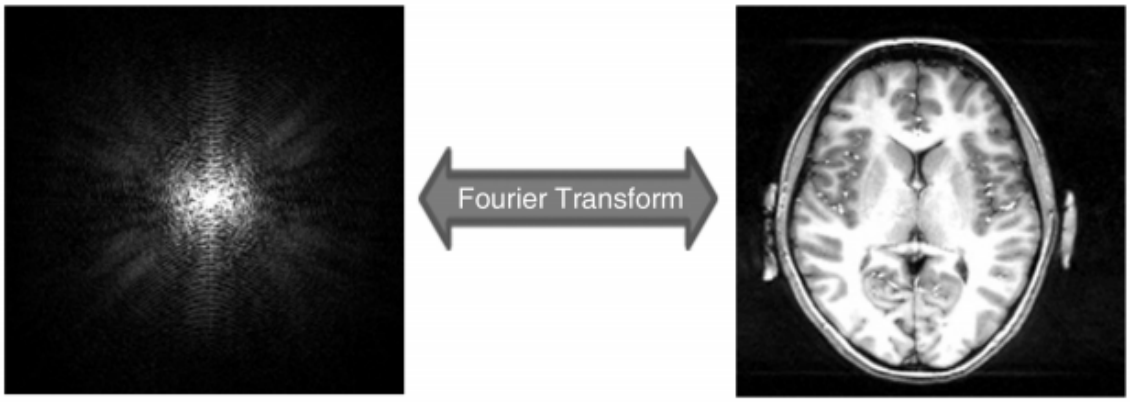
A. Quartered
B. Halved
C. Doubled
D. Quadrupled

Answer: A – Quartered

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Runge & Heverhagen. (2022) *The Physics of Clinical MR Taught Through Images*

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



(Image Credit: [5]Qureshi. (2017) *Journey through k-space: an interactive educational tool*

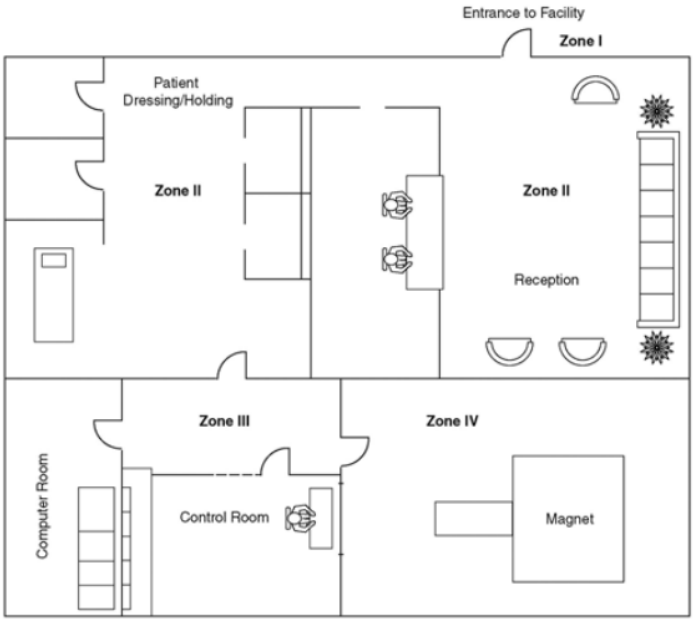
A. Center of k-space
B. Peripheral part of k-space
C. Left half of the k-space
D. Right half of the k-space

Answer: B – Peripheral part of the k-space

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Sensakovic & Huda. (2023) *Review of Radiologic Physics*; [6]Hashemi. (2017) *MRI: The Basics*; [7]McRobbie. (2017) *MRI from Picture to Proton*

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



(Image Credit: [8]Kanal. (2007) *ACR guidance document for safe MR practices: 2007*

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

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

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

References:[8]Kanal. (2007) *ACR guidance document for safe MR practices: 2007*; [9]ACR Committee on MR Safety. (2020) *ACR guidance document on MR safe practices: Updates and critical information 2019*; [10]Zhuo & Gullapalli. (2006) *MR artifacts, safety, and quality control*; [11]McRobbie. (2020) *Essentials of MRI safety*; [12]Expert Panel on MR Safety. (2013) *ACR guidance document on MR safe practices: 2013*

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

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

Answer: C – Thermal injuries

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

References:[13]Hardy & Weil. (2010) *A review of thermal MR injuries*

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

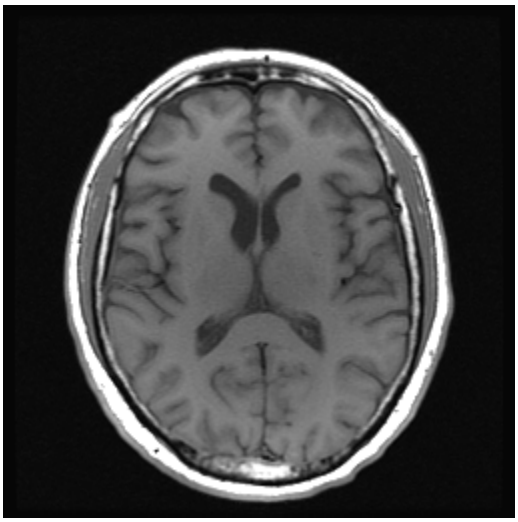
A. Yes, the pacemaker can be safely scanned under any conditions (e.g., field strength, SAR)
B. Yes, the pacemaker may be safely scanned under specific conditions (e.g., field strength, SAR)
C. No, the pacemaker cannot be safely scanned, and the patient should be referred for other imaging
D. Undetermined;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

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

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

References:[9]ACR Committee on MR Safety. (2020) *ACR guidance document on MR safe practices: Updates and critical information 2019*; [11]McRobbie. (2020) *Essentials of MRI safety*

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



(Image courtesy of Ping Hou, PhD, MD Anderson Cancer Center)

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

Answer: A – Short TR, Short TE

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Runge & Heverhagen. (2022) *The Physics of Clinical MR Taught Through Images*

Q8. (Effective Use) What method of fat suppression results in the most robust reduction in fat signal for a patient with an MR safe metal implant?

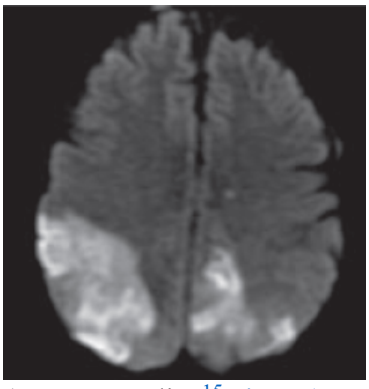
A. Spectral selective fat suppression
B. STIR technique
C. Saturation Band
D. DIXON method

Answer: B – STIR technique

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [14]Dixon. (1984) *Simple proton spectroscopic imaging*

Q9. (Effective Use) A spin echo EPI diffusion-weighted image (see below) is a combination of diffusion weighting and what other contrast?



(Image Credit: [15]Bitar. (2006) *MR pulse sequences: what every radiologist wants to know but is afraid to ask*)

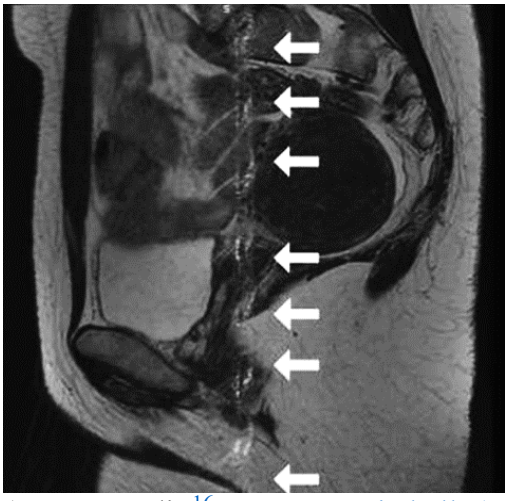
A. T1 weighting
B. T2 weighting
C. T2/T1 weighting
D. Proton density weighting

Answer: B – T2 weighting

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Runge & Heverhagen. (2022) *The Physics of Clinical MR Taught Through Images*

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



(Image Credit:[16]Graves & Mitchell. (2013) *Body MRI artifacts in clinical practice: a physicist's and radiologist's perspective*)

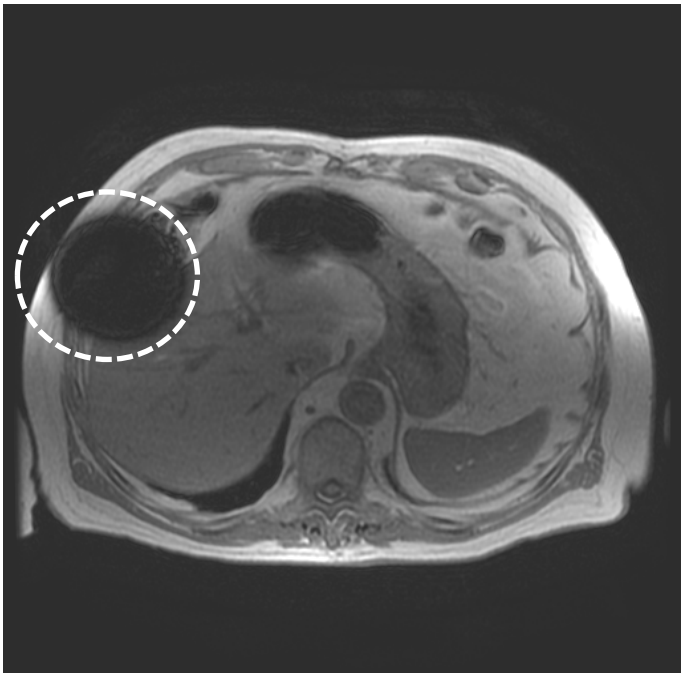
A. Motion artifacts
B. RF interference from the environment
C. Peripheral signal artifacts
D. Bad RF coil

Answer: C – Peripheral signal artifacts

Explanation: It is not motion artifacts (choice A), since there is no anatomic replicate in the phase encoding direction. If it were RF interference (choice B) from the environment, the zipper or ghost would extend in the frequency-encoding direction and would not change position from slice to slice. If it was a bad RF coil (choice D) then we would expect some shading at the same location for each slice, but there is no SNR drop at all. Peripheral signal artifacts appear as either bright spots or as ribbons (ghost) of signal smeared through the image in the phase-encoding direction. We refer to these artifacts as Star artifacts (bright spot) or Annefacts (ribbons). It is all due to anatomy within the active volume of the coil, but outside the FOV and the receivers can detect them. This happens more with multi-channel coil when the FOV is located close to the edge of (lower part of the coil in this case) coil, especially when saturation RF applied. The artifacts could have been prevented/reduced by (1) keeping the image FOV far from the edge of the sensitive region of the receive coil; (2) swapping the phase encoding direction; (3) removing the spatial saturation RF pulse.

References:[16]Graves & Mitchell. (2013) *Body MRI artifacts in clinical practice: a physicist's and radiologist's perspective*

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



(Image courtesy of Ping Hou, PhD, MD Anderson Cancer Center)

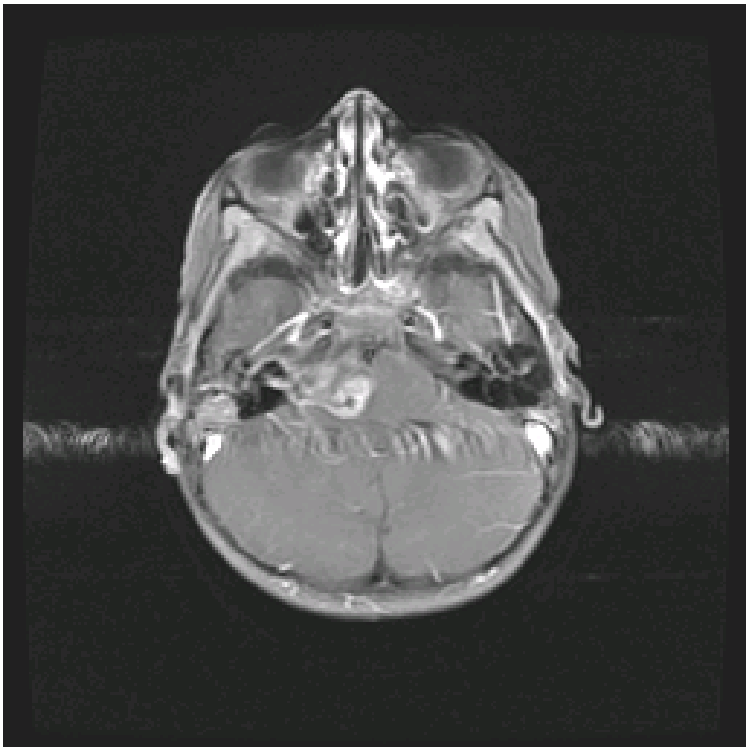
A. Use flow suppression
B. Use a spin echo sequence
C. Increase TE
D. Increase TR

Answer: B – Use a spin echo sequence

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [17]Arena. (1995) *MR imaging artifacts that simulate disease: how to recognize and eliminate them*; [18]Elster. (2024) *Questions and Answers in MRI*

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



(Image courtesy of Ping Hou, PhD, MD Anderson Cancer Center)

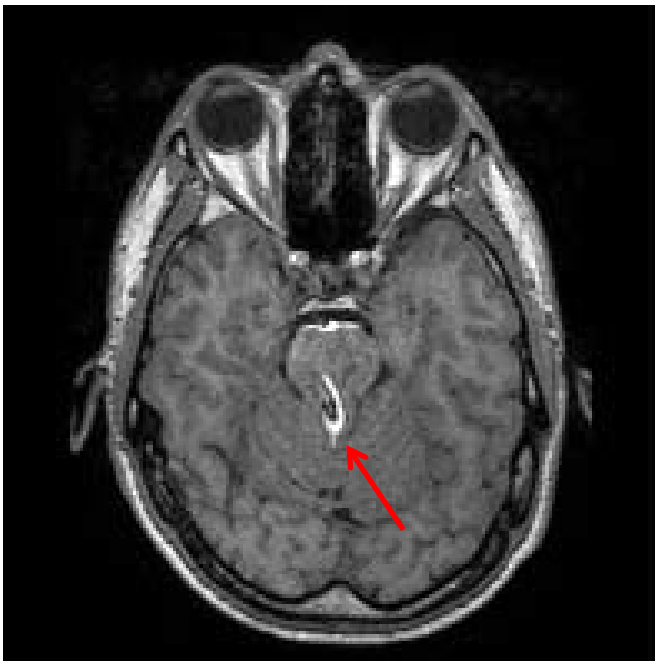
A. Patient motion
B. Flow
C. RF interference
D. Gradient failure

Answer: B – Flow artifact

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

References:[17]Arena. (1995) *MR imaging artifacts that simulate disease: how to recognize and eliminate them*; [18]Elster. (2024) *Questions and Answers in MRI*; [19]Edelman & Hesselink. (2005) *Clinical Magnetic Resonance Imaging*

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



(Image courtesy of Trevor Andrews, PhD, Washington University School of Medicine in St. Louis)

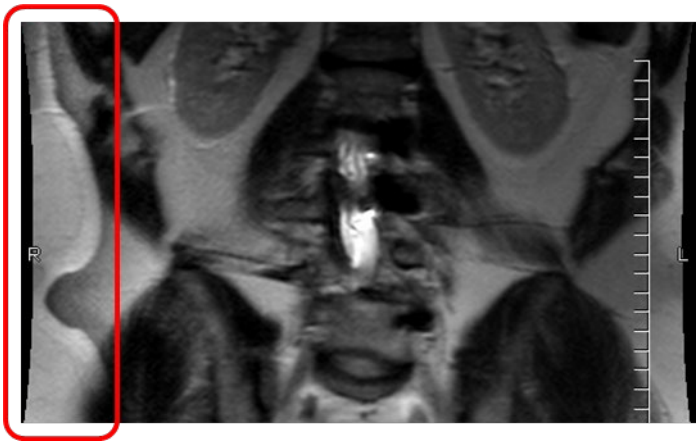
A. Flow artifact
B. Gibbs ringing
C. RF interference
D. Aliasing

Answer: D – Aliasing

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

References:[17]Arena. (1995) *MR imaging artifacts that simulate disease: how to recognize and eliminate them*; [18]Elster. (2024) *Questions and Answers in MRI*

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



(Image courtesy of Trevor Andrews, PhD, Washington University School of Medicine in St. Louis)

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

Answer: D – Increase FOV

Explanation: Aliasing artifacts happen because the size of the object is larger than the FOV. It is a consequence of Nyquist theory: the sampling rate must be at least twice the highest frequency expected, $f_{aliased} = f_{true} - 2f_{Nyquist}$. 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 at the cost of spatial resolution. Increasing TR or decreasing TE would change the contrast but not remove the artifact. Decreasing NEX will reduce SNR, but not impact this artifact.

References:[18]Elster. (2024) *Questions and Answers in MRI*; [19]Edelman & Hesselink. (2005) *Clinical Magnetic Resonance Imaging*; [20]ACR. (2020) *ACR Manual on MR Safety*

Q15. (Safety, Quality Management, and Regulatory Issues) Specific Absorption Rate (SAR) is the power deposited to certain amount of tissue, with a unit of watts per kilogram. What is the SAR limitation of head and body for the normal operating mode?

A. Maximum whole-body SAR 2.0 W/kg, Head SAR 3.2 W/kg.
B. Maximum whole-body SAR 3.2 W/kg, Head SAR 2.0 W/kg.
C. Maximum whole-body SAR 4.0 W/kg, Head SAR 3.2 W/kg.
D. There is no limitation.

Answer: A – International Electrotechnical Commission (IEC) Standard for MRI normal mode is whole body 2.0w/kg, head 3.2W/kg

Explanation: Whole-body SAR of 4.0 W/kg and head 3.2 W/kg is the first-level operating mode. Even though these regulatory limits exist, it is important to note each vendor may have different SAR calculation method. The number of SAR reported on each scanner should not be considered as a solid "limit" on safety, it is for reference only. Some manufacture offers low SAR mode, normal operating mode and first level operating mode.

References:[21]Allison & Yanasak. (2015) *What MRI sequences produce the highest specific absorption rate (SAR), and is there something we should be doing to reduce the SAR during standard examinations?*

Q16. (Safety, Quality Management, and Regulatory Issues) A scheduled patient has an implanted spinal cord stimulator with an MR Conditional whole-body SAR limit of 1 W/kg for 60 min of active scanning at 1.5T or 3T. Which of the following methods would be useful for achieving that goal for a lumbar spine exam without Gd contrast?

A. Reduce TR
B. Reduce bandwidth
C. Add saturation bands
D. Reduce refocus flip angle

Answer: D – Reduce refocus flip angle

Explanation: SAR is increased with RF-induced heating. TR must be increased to reduce SAR by spreading RF energy deposition over more time. Bandwidth has at most a small indirect effect upon SAR. Adding saturation bands adds additional RF pulses to the scan and only increases SAR. The contribution to SAR from an RF pulse increases with the square of the flip angle, so reducing RF flip angles can strongly reduce SAR.

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Runge & Heverhagen. (2022) *The Physics of Clinical MR Taught Through Images*

MODULE 9: ULTRASOUND

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

Fundamental Knowledge:

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

Clinical Applications and Problem Solving:

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

Curriculum:

9. Ultrasound

9.1. Underlying Technology and Physics Principles [3]

- 9.1.1. Basic Sound Wave Concepts [3]
  - 9.1.1.1. Definition of Sound and Ultrasound [2]
  - 9.1.1.2. Sound Wave Propagation [3]
  - 9.1.1.3. Longitudinal and Transverse Waves [2]
- 9.1.2. Sound Wave Properties [3]
  - 9.1.2.1. Wavelength, Frequency, Period, Speed, and Velocity [3]
  - 9.1.2.2. Density and Pressure Changes in Materials [3]
  - 9.1.2.3. Compressibility and Elasticity [3]
  - 9.1.2.4. Dependence of Sound Speed on Medium and Properties [3]
- 9.1.3. Power and Intensity [3]
  - 9.1.3.1. Decibel Scale [3]

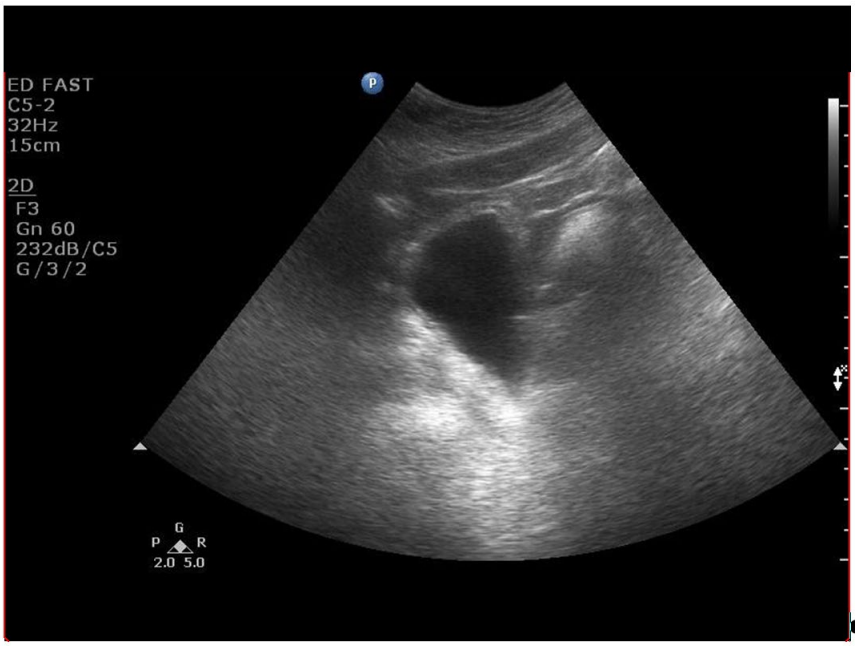
Module Specific References

1. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
2. Hedrick, W. R., Hykes, D. L., & Starchman, D. E. (2004). *Ultrasound Physics and Instrumentation* (4th ed.). Mosby
3. Prabhu, S. J., et al. (2014). Ultrasound artifacts: Classification, applied physics with illustrations, and imaging appearances. *Ultrasound Quarterly*, *30*(2), 145-157,

4. Wolbarst, A. (2005). *Physics of Radiology* (2nd ed.). Medical Physics Publishing Corportation.
5. Pozniak, M. A., Zagzebski, J. A., & Scanlan, K. A. (1992). Spectral and color Doppler artifacts. *Radiographics*, *12*(1), 35-44,
6. Mustafa, A., et al. (2023). *RSNA Physics Modules - Ultrasound Image Acquisition and Doppler Ultrasound (2023)*. Radiological Society of North America. https://education.rsna.org/diweb/catalog/item/eid/1325983381
7. Revzin, M. V., et al. (2019). Optimizing image quality when evaluating blood flow at doppler US: A tutorial. *Radiographics*, *39*(5), 1501-1523,
8. Anvari, A., Forsberg, F., & Samir, A. E. (2015). A primer on the physical principles of tissue harmonic imaging. *Radiographics*, *35*(7), 1955-1964,
9. Bushong, S. C. (2021). *Radiologic Science for Technologists: Physics, Biology, and Protection* (12th ed.). Elsevier.
10. Kruskal, J. B., Newman, P. A., Sammons, L. G., & Kane, R. A. (2004). Optimizing doppler and color flow US: Application to hepatic sonography. *Radiographics*, *24*(3), 657-675,
11. Szabo, T. L., & Lewin, P. A. (2013). Ultrasound transducer selection in clinical imaging practice. *Journal of Ultrasound in Medicine*, *32*(4), 573-582,
12. Hindi, A., Peterson, C., & Barr, R. G. (2013). Artifacts in diagnostic ultrasound [Report]. *Reports in Medical Imaging*, *6*, 29+,
13. Baad, M., Lu, Z. F., Reiser, I., & Paushter, D. (2017). Clinical significance of US artifacts. *Radiographics*, *37*(5), 1408-1423,
14. Owen, C. C., & Bilhartz, L. E. (2003). Gallbladder polyps, cholesterolosis, adenomyomatosis, and acute acalculous cholecystitis. Seminars in gastrointestinal disease,
15. Kasraie, N., et al. (2022). *RSNA Physics Modules - Ultrasound – Concepts and Transducers (2022)*. Radiological Society of North America. https://education.rsna.org/diweb/catalog/item/eid/1311751622
16. Feldman, M. K., Katyal, S., & Blackwood, M. S. (2009). US artifacts. *Radiographics*, *29*(4), 1179-1189,
17. Abbott, J. G. (1999). Rationale and derivation of MI and TI—a review. *Ultrasound in medicine & biology*, *25*(3), 431-441,
18. Houston, L. E., Allsworth, J., & Macones, G. A. (2011). Ultrasound is safe... right? Resident and maternal-fetal medicine fellow knowledge regarding obstetric ultrasound safety. *Journal of Ultrasound in Medicine*, *30*(1), 21-27,
19. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.
20. Kremkau, F. W. (2020). *Sonography principles and instruments E-Book* (10th ed.). Elsevier Health Sciences.

Example Q&A:

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



(Image courtesy of Adel Mustafa, PhD, Yale School of Medicine)

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

Answer: B – Decreased attenuation

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Hedrick. (2004) *Ultrasound Physics and Instrumentation*; [3]Prabhu. (2014) *Ultrasound artifacts: Classification, applied physics with illustrations, and imaging appearances*

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

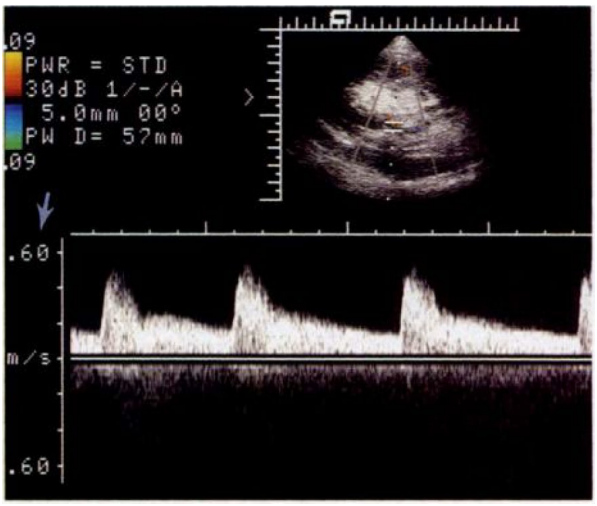
A. 3 dB
B. 5 dB
C. 7.5 dB
D. 10 dB

Answer: D – 10 dB

Explanation: Using the rule of the thumb for attenuation in soft tissue of 0.5 dB/cm/MHz, the attenuation would be: 0.5 dB/cm/Hz × 5 MHz × 4 cm = 10 dB.

References:[2]Hedrick. (2004) *Ultrasound Physics and Instrumentation*; [4]Wolbarst. (2005) *Physics of Radiology*

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



(Image Credit: [5]Pozniak. (1992) *Spectral and color Doppler artifacts*

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

Answer: B – Variations in signal intensity

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Wolbarst. (2005) *Physics of Radiology*; [6]Mustafa. (2023) *RSNA Physics Modules - Ultrasound Image Acquisition and Doppler Ultrasound (2023)*; [7]Revzin. (2019) *Optimizing image quality when evaluating blood flow at doppler US: A tutorial*

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

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

Answer: B – Enhanced contrast to noise

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

References:[2]Hedrick. (2004) *Ultrasound Physics and Instrumentation*; [4]Wolbarst. (2005) *Physics of Radiology*; [8]Anvari. (2015) *A primer on the physical principles of tissue harmonic imaging*

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

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

Answer: C – Expanded field of view

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

References:[9]Bushong. (2021) *Radiologic Science for Technologists: Physics, Biology, and Protection*; [10]Kruskal. (2004) *Optimizing doppler and color flow US: Application to hepatic sonography*; [11]Szabo & Lewin. (2013) *Ultrasound transducer selection in clinical imaging practice*

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

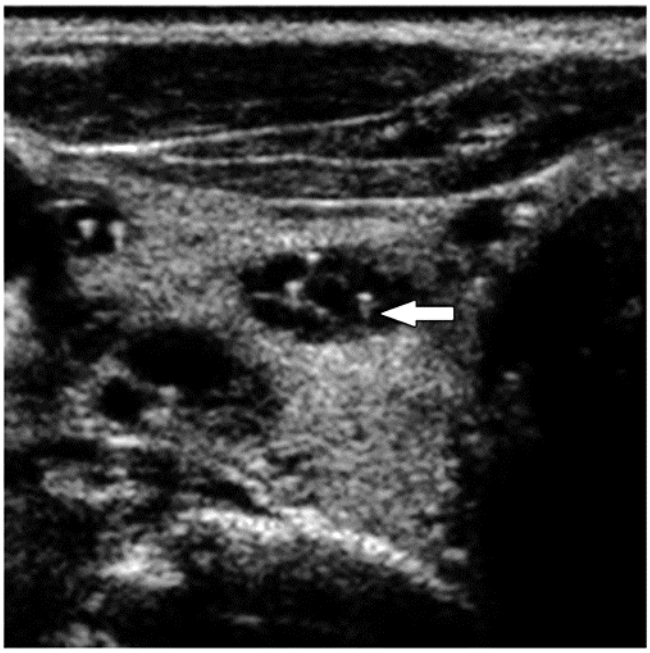
A. 15°
B. 25°
C. 55°
D. 75°

Answer: C – 55°

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [10]Kruskal. (2004) *Optimizing doppler and color flow US: Application to hepatic sonography*; [12]Hindi. (2013) *Artifacts in diagnostic ultrasound*

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



(Image Credit: [13]Baad. (2017) *Clinical significance of US artifacts*)

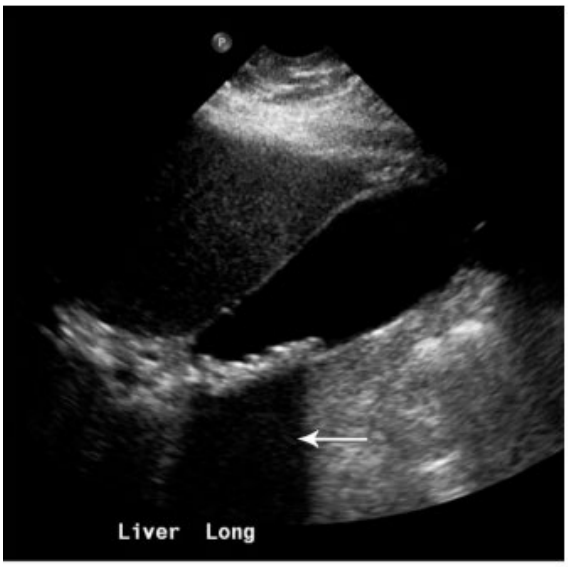
A. Mirror image artifact
B. Shadowing artifact
C. Comet tail artifact
D. Side lobe artifact

Answer: C – Comet tail artifact

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

References:[2]Hedrick. (2004) *Ultrasound Physics and Instrumentation*; [3]Prabhu. (2014) *Ultrasound artifacts: Classification, applied physics with illustrations, and imaging appearances*; [13]Baad. (2017) *Clinical significance of US artifacts*; [14]Owen & Bilhartz. (2003) *Gallbladder polyps, cholesterolosis, adenomyomatosis, and acute acalculous cholecystitis*; [15]Kasraie. (2022) *RSNA Physics Modules - Ultrasound – Concepts and Transducers (2022)*

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



(Image Credit:[16]Feldman. (2009) *US artifacts*)

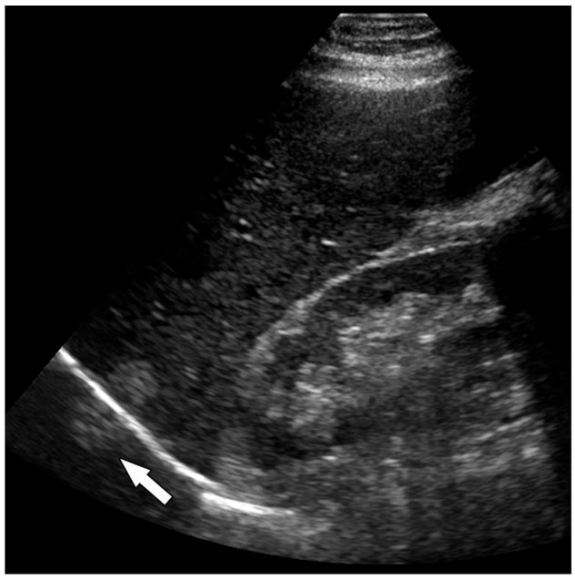
A. Comet tail
B. Mirror image
C. Shadowing
D. Twinkle

Answer: C – Shadowing

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

References:[3]Prabhu. (2014) *Ultrasound artifacts: Classification, applied physics with illustrations, and imaging appearances*; [9]Bushong. (2021) *Radiologic Science for Technologists: Physics, Biology, and Protection*; [12]Hindi. (2013) *Artifacts in diagnostic ultrasound*

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



(Image Credit: {Baad, 2017 #191)

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

Answer: A – Mirror image

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

References:{Bushong, 2021 #145;Hedrick, 2004 #197;Prabhu, 2014 #198}

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

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

Answer: D – Inversely proportional to the square root

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [17]Abbott. (1999) *Rationale and derivation of MI and TI—a review*; [18]Houston. (2011) *Ultrasound is safe... right? Resident and maternal-fetal medicine fellow knowledge regarding obstetric ultrasound safety*

Q11. (Underlying Technology and Physics Principles) What is the wavelength of a 1.5 MHz wave in soft tissue?

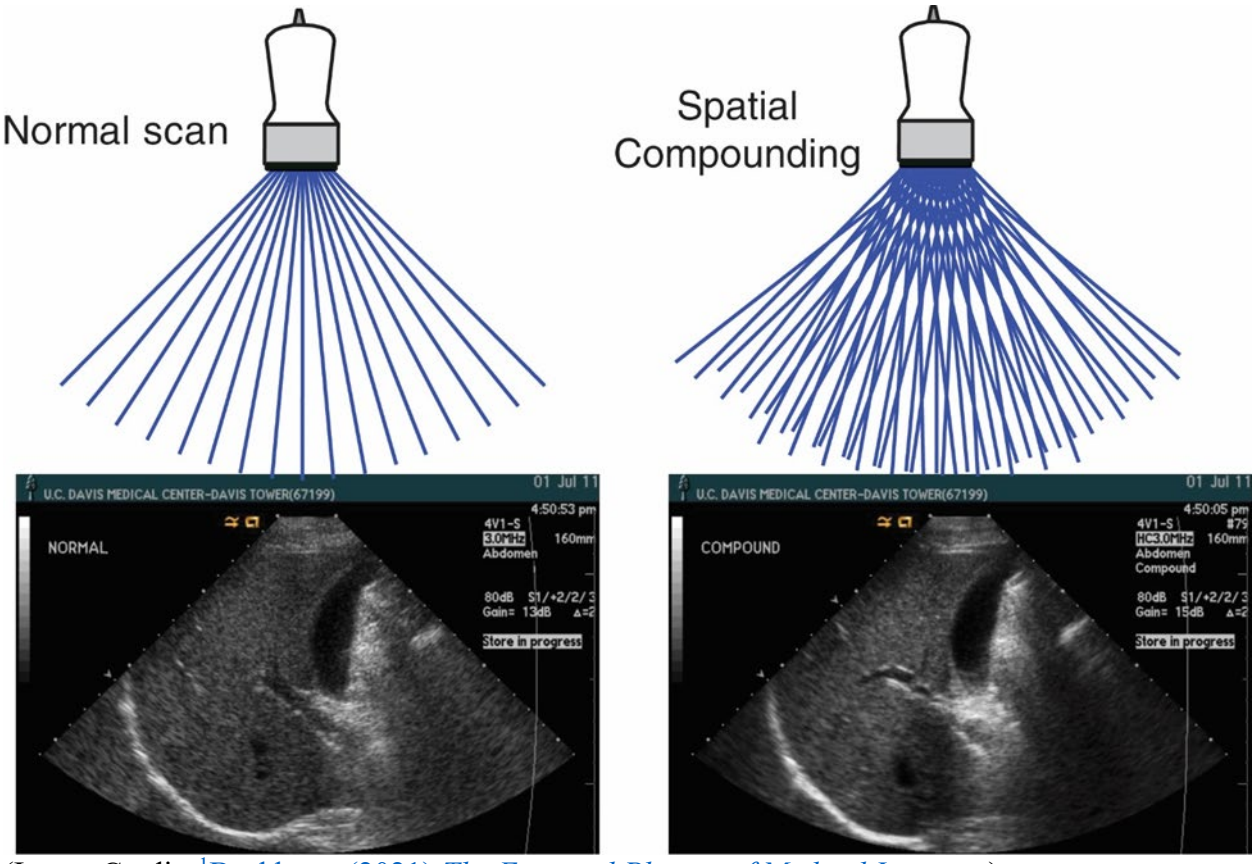
A. 15 mm
B. 10 mm
C. 1.5 mm
D. 1.0 mm
E. 0.15 mm

Answer: D – 1.0 mm

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [19]Sensakovic & Huda. (2023) *Review of Radiologic Physics*; [20]Kremkau. (2020) *Sonography principles and instruments E-Book*

Q12. (Effective Use) What is a disadvantage of spatial compounding compared to normal scan mode?



(Image Credit: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*)

A. Reduced signal-to-noise ratio
B. Increased spatial blurring of moving objects
C. Increased prominence of speckle noise
D. Reduced depth of penetration

Answer: B – Increased spatial blurring of moving objects

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Wolbarst. (2005) *Physics of Radiology*; [9]Bushong. (2021) *Radiologic Science for Technologists: Physics, Biology, and Protection*

MODULE 10: RADIONUCLIDE PRODUCTION, RADIOPHARMACEUTICALS, AND NON-IMAGING INSTRUMENTATION

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

Fundamental Knowledge:

1. Describe the modes of radioactive decay and resulting emissions.
2. Describe methods of radionuclide production and quality control (QC) tests.
3. Identify common radionuclides and their characteristics (e.g., modes of decay, energy of emissions, half-life).
4. Properties of ideal radiopharmaceuticals for imaging and therapy.
5. Identify uptake mechanisms of commonly used radiopharmaceuticals.
6. Describe radiopharmaceutical bio-distribution and the impact on radiation dose.
7. Describe the basic operation of instruments commonly used for measuring and calibrating radioactivity and related QC.

Clinical Applications and Problem Solving:

1. Compare ideal characteristics of imaging versus therapeutic radiopharmaceuticals.
2. Determine the indications and radiopharmaceutical activity administered to adults and pediatric patients for various imaging procedures.

Curriculum:

10. Radionuclide Production, Radiopharmaceuticals, and Non-Imaging Instrumentation

10.1. Underlying Technology and Physics Principles [3]

- 10.1.1. Radionuclide Decay and Emissions (see Module 1) [3]
- 10.1.2. Radionuclide Production [2]
  - 10.1.2.1. Reactor-Produced Radionuclides [2]
    - 10.1.2.1.1. Principle of Operation [1]
    - 10.1.2.1.2. Fission Products (e.g., ^{99}Mo, ^{131}I, ^{133}Xe) [2]
    - 10.1.2.1.3. Neutron-Activation Products (e.g., ^{89}Sr, ^{177}Lu, ^{223}Ra) [2]
  - 10.1.2.2. Cyclotron-Produced Radionuclides [2]
    - 10.1.2.2.1. Principle of Operation [1]
    - 10.1.2.2.2. Positron Emitting Isotopes [3]
  - 10.1.2.3. Radionuclide Generators [3]
    - 10.1.2.3.1. ^{99}Mo – ^{99m}Tc Generator [3]
    - 10.1.2.3.2. Other Generators (e.g.,^{82}Sr – ^{82}Rb, ^{68}Ge – ^{68}Ga) [2]
    - 10.1.2.3.3. Elution and Quality Control [3]
  - 10.1.2.4. Specific Activity and Tracer Principle [2]
- 10.1.3. Radiopharmaceuticals [3]
  - 10.1.3.1. Ideal Characteristics of a Radiopharmaceutical [3]
  - 10.1.3.2. Radiolabeling and Preparation [2]
  - 10.1.3.3. Quality Assurance and Quality Control Procedures [3]
    - 10.1.3.3.1. Radionuclidic Purity [2]

- 10.1.3.3.2. Chemical Purity [2]
- 10.1.3.3.3. Radiochemical Purity [2]
- 10.1.4. Counting Statistics [1]
  - 10.1.4.1. Poisson Distribution [1]
  - 10.1.4.2. Propagation of Error (Gross, Net, and Background Counts) [1]
  - 10.1.4.3. Uncertainty, Standard Deviation and Coefficient of Variation [1]

10.2. Effective Use [3]
- 10.2.1. Non-imaging Radionuclide Studies (e.g., Thyroid Uptake, GFR) [2]
- 10.2.2. ^{99m}Tc-labeled Radiopharmaceuticals [3]
- 10.2.3. Other Gamma- and Positron-Emitter-Labeled Radiopharmaceuticals [3]
- 10.2.4. Theranostics [3]
- 10.2.5. Radiopharmaceuticals for Therapy (e.g., ^{131}I Sodium Iodide, ^{90}Y Microspheres, ^{223}Ra Dichloride, ^{177}Lu-dotatate, ^{177}Lu-PSMA) (see Module 14) [3]
- 10.2.6. Typical Dosages for Common Clinical Studies [3]
- 10.2.7. Uptake, Distribution, and Clearance Kinetics [3]

10.3. Safety, Quality Management, and Regulatory Issues [3]
- 10.3.1. Internal Dose Assessment [3]
  - 10.3.1.1. Physical, Biological, and Effective Half-Life [3]
  - 10.3.1.2. MIRD and RADAR Formalism [3]
- 10.3.2. Radiation Detection Instrumentation [3]
  - 10.3.2.1. Gas-Filled Detectors [3]
    - 10.3.2.1.1. Mechanisms of Operation [3]
    - 10.3.2.1.2. Applications and Limitations [3]
    - 10.3.2.1.3. Survey Meters (e.g., GM Counter, Ionization Chamber) [3]
    - 10.3.2.1.4. Dose Calibrator [3]
    - 10.3.2.1.5. Quality Control [3]
  - 10.3.2.2. Scintillation Detectors [3]
    - 10.3.2.2.1. Mechanisms of Operation [3]
    - 10.3.2.2.2. Applications and Limitations [3]
    - 10.3.2.2.3. Pulse-Height Spectroscopy [3]
    - 10.3.2.2.4. Thyroid Probe [3]
    - 10.3.2.2.5. Well Counter [3]
    - 10.3.2.2.6. Liquid Scintillation Counter [2]
    - 10.3.2.2.7. Quality Control [3]
  - 10.3.2.3. Semiconductor Detectors [2]
  - 10.3.2.4. Photomultiplier Tube (PMT) [3]

Module Specific References

1. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
2. MIRD. (1975). MIRD Dose Estimate Report No. 5. Summary of current radiation dose estimates to humans from 123I, 124I, 125I, 126I, 130I, 131I, and 132I as sodium iodide. *J. Nucl. Med*, *16*, 857-860,
3. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.

4. Cherry, S. A., Sorenson, J. A., & Phelps, M. E. (2012). *Physics in Nuclear Medicine* (4th ed.). Saunders Elsevier.
5. Mettler, F. A., & Guiberteau, M. J. (2018). *Essentials of Nuclear Medicine and Molecular Imaging* (7th ed.). Elsevier Health Sciences.
6. Saha, G. B. (2018). *Fundamentals of Nuclear Pharmacy* (7th ed.). Springer.
7. Bartel, T. B., et al. (2018). SNMMI procedure standard for bone scintigraphy 4.0. *Journal of nuclear medicine technology*, *46*(4), 398-404,
8. Chandra, R., & Rahmim, A. (2017). *Nuclear Medicine Physics: The Basics* (8th ed.). Lippincott Williams & Wilkins.

Example Q&A:

Q1. (Underlying Technology and Physical Principles) Why does ^{131}I deliver 100 times more dose to the thyroid per mCi than ^{123}I?

A. Higher-energy gamma radiation
B. Abundance of beta radiation
C. Longer half-life
D. Greater specific activity

Answer: B – Abundance of beta radiation

Explanation: Beta particles are only emitted from ^{131}I. These are highly energetic and deposit their dose less than a centimeter from the source.

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]MIRD. (1975) *MIRD Dose Estimate Report No. 5. Summary of current radiation dose estimates to humans from 123I, 124I, 125I, 126I, 130I, 131I, and 132I as sodium iodide*

Q2. (Underlying Technology and Physical Principles) What is the effective half-life of ^{99m}Tc in an organ if its biological half-life is 3 hours?

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

Answer: A – 2 hours

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q3. (Safety, Quality Management, and Regulatory Issues) What is the purpose of photomultiplier tubes in nuclear medicine instrumentation?

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

Answer: B – Convert visible light into electrical signal

Explanation: PMTs are constructed with a photocathode followed by a series of dynodes. The role of the photocathode is to convert light from crystal excitation to a proportionate number of electrons. Then the dynodes amply the signal by a factor of approximately 10^6.

References: [4]Cherry. (2012) *Physics in Nuclear Medicine*

Q4. (Underlying Technology and Physical Principles) Which of the following radionuclides is produced using a generator?

A. ^{99}Mo
B. ^{131}I
C. ^{99m}Tc
D. ^{177}Lu

Answer: C – ^{99m}Tc

Explanation: The most common generator system is a ^{99}Mo-^{99m}Tc generator. The parent radionuclide, ^{99}Mo, is affixed to a column and decays to its daughter radionuclide ^{99m}Tc. The ^{99m}Tc is then eluted from the generator.

References:[5]Mettler & Guiberteau. (2018) *Essentials of Nuclear Medicine and Molecular Imaging*

Q5. (Effective Use) Which of the following is a radionuclidic impurity in a ^{99m}Tc elution?

A. ^{99}Mo breakthrough
B. Aluminum breakthrough
C. $^{99m}TcO_2$
D. H_2O_2

Answer: A – ^{99}Mo breakthrough

Explanation: ^{99}Mo contamination in the ^{99m}Tc-eluate increases radiation dose and reduces image quality without providing any benefit to the patient. The amount of ^{99}Mo present at the time of administration must be < 0.15 μCi/mCi ^{99m}Tc. The desired form of ^{99m}Tc after elution is $^{99m}TcO_4$—. Any other form, such as $^{99m}TcO_2$, is a radiochemical impurity. Aluminum breakthrough, which is limited to 10 μg Al/ml ^{99m}Tc for fission-produced ^{99}Mo, is a chemical impurity. In wet generators, the radiolysis of water can cause the formation of hydrogen peroxide (H_2O_2) and a perhydroxyl free radical.

References:[6]Saha. (2018) *Fundamentals of Nuclear Pharmacy*

Q6. (Effective Use) What is a typical adult dosage of ^{99m}Tc-labeled diphosphonates for a bone scan?

A. 2 mCi
B. 20 mCi
C. 200 mCi
D. 2000 mCi

Answer: B – 20 mCi

Explanation: The typical administered activity of ^{99m}Tc-labeled diphosphonates for a bone scan is 500 – 1,110 MBq (~13 – 30 mCi) for adults and 170 – 210 MBq (~4 – 6 mCi) for children.

References: [5]Mettler & Guiberteau. (2018) *Essentials of Nuclear Medicine and Molecular Imaging*; [7]Bartel. (2018) *SNMMI procedure standard for bone scintigraphy 4.0*

Q7. (Underlying Technology and Physical Principles) What is the approximate physical half-life of ^{18}F?

A. 75 seconds
B. 110 minutes
C. 6 hours
D. 8 days

Answer: B – 110 minutes

Explanation: ^{18}F decays by positron emission and has a half-life of 110 minutes. ^{82}Rb decays by positron emission and has a half-life of 75 seconds. ^{99m}Tc decays by isomeric transition with a half-life of 6 hours. ^{131}I decays by β- emission and isomeric transition with a half-life of 8 days.

References: [5]Mettler & Guiberteau. (2018) *Essentials of Nuclear Medicine and Molecular Imaging*

Q8. (Safety, Quality Management, and Regulatory Issues) The effective half-life of a radiopharmaceutical is:

A. The sum of the physical and biologic half-life
B. Always longer than the physical or biologic half-life
C. Always shorter than the physical or biologic half-life
D. Shorter than the physical half-life, but longer than the biologic half-life

Answer: C – Always shorter than the physical or biological half-life

Explanation: The effective half-life, $T_e = (T_p \times T_b)/(T_p + T_b)$, incorporates both the physical and biologic half-lives and is always shorter than either the physical or biologic half-life.

References: [5]Mettler & Guiberteau. (2018) *Essentials of Nuclear Medicine and Molecular Imaging*; [8]Chandra & Rahmim. (2017) *Nuclear Medicine Physics: The Basics*

Q9. (Safety, Quality Management, and Regulatory Issues) Which type of detector consists of a single sodium iodide crystal, a PMT on the end, and a single hole collimator limited to counting very low activities?

A. Dose calibrator
B. Gamma camera
C. GM counter
D. Thyroid probe

Answer: D – Thyroid probe

Explanation: A thyroid probe is a single probe counting system used for measuring thyroid uptake of radioactive iodine. It is similar to a well counter in concept, but does not have a central hole in the sodium iodide crystal.

References: [5]Mettler & Guiberteau. (2018) *Essentials of Nuclear Medicine and Molecular Imaging*

Q10. (Safety, Quality Management, and Regulatory Issues) Which type of detector is a highly sensitive, gas filled detector used to measure low levels of radiation, but can suffer from "dead time"?

A. Dose calibrator
B. Well counter
C. GM counter
D. Thyroid probe

Answer: C – GM counter

Explanation: A GM counter is a gas filled detector used to measure low levels of radiation. It is not as useful in high radiation fields as it suffers from dead time. They are unable to differentiate between different types of radiation and they cannot determine the exact energy of the detected radiation.

References:[5]Mettler & Guiberteau. (2018) *Essentials of Nuclear Medicine and Molecular Imaging*

MODULE 11: GAMMA CAMERA

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

Fundamental Knowledge:

1. Understand the principles of operation of a gamma camera.
2. Understand the major components and their functions.
3. Understand key instrumentation quality control tests.
4. Understand Nuclear Regulatory Commission (NRC)/Agreement State regulations related to gamma cameras.

Clinical Applications and Problem Solving:

1. Describe common image artifacts and methods to minimize them.
2. Describe how selection of image acquisition parameters affects image quality.

Curriculum:

11. Gamma Camera
11.1. Technology and Physical Principles [3]
    11.1.1. Principles of Operation [3]
    11.1.2. Gamma Camera Components (Crystal, Collimator, Light Pipe, Photomultiplier Tubes, Position Circuits, Pulse Height Analyzer) [3]
        11.1.2.1. Crystal Parameters (Scintillator Characteristics) [3]
        11.1.2.2. Spatial Localization (Anger Positioning Logic) [2]
        11.1.2.3. Collimator Types and Characteristics [3]
            11.1.2.3.1. Parallel Hole, Pinhole, and Other Geometries [3]
            11.1.2.3.2. Sensitivity [3]
            11.1.2.3.3. Resolution [3]
            11.1.2.3.4. Energy Specification (Low Energy, Low Energy High Resolution, Medium Energy, High Energy) [3]
        11.1.2.4. New Technology (e.g., Solid-State Detectors) [2]
    11.1.3. Image Acquisition (Static, Dynamic, Gated, Matrix Size, Count Rate and Administered Activity Considerations) [3]
    11.1.4. Image Processing [3]
        11.1.4.1. Spatial and Temporal Filtering [2]
        11.1.4.2. Frame Manipulation (e.g., Subtraction) [2]
        11.1.4.3. Region of Interest and Time-Activity Curves [2]
11.2. Image Characteristics and Artifacts [3]
    11.2.1. Spatial Resolution [3]
    11.2.2. Sensitivity [3]
    11.2.3. Noise and Signal/Noise ratio [3]
    11.2.4. Count Rate and Administered Activity Considerations [3]
    11.2.5. Artifacts [3]
        11.2.5.1. Instrumentation Sources (e.g., Non-uniformity, Collimator, Improper Energy Peaking, etc.) [3]
        11.2.5.2. Patient Sources (Motion, Foreign Objects, etc.) [3]

11.3. Effective Use [3]
- 11.3.1. Clinical Quantitative Imaging [3]
  - 11.3.1.1. Thyroid [3]
  - 11.3.1.2. Renal [3]
  - 11.3.1.3. Cardiac (Ejection Fraction, Myocardial Perfusion) [3]
  - 11.3.1.4. Ventilation/Perfusion (V/Q) [3]
  - 11.3.1.5. Multi-Energy Imaging (111In, 67Ga) [3]
  - 11.3.1.6. Gallbladder (Ejection Fraction) [3]
  - 11.3.1.7. Gastric Emptying [3]
  - 11.3.1.8. Bone [3]
- 11.3.2. Radiopharmaceutical Administered Activity [3]
  - 11.3.2.1. Typical Adult and Pediatric Dosage [3]
  - 11.3.2.2. SNMMI – EANM Consensus Guidelines on Pediatric Administered Activities [2]
  - 11.3.2.3. Pregnancy and Breastfeeding Considerations (e.g., Reduced Activity for Lung Perfusion Scans for Pregnant Patients) [3]

11.4. Safety, Quality Management, and Regulatory Issues [3]
- 11.4.1. Gamma Camera Quality Control (Extrinsic and Intrinsic) [3]
  - 11.4.1.1. Energy Spectrum/Radionuclide Photopeak Peaking [3]
  - 11.4.1.2. Uniformity [3]
  - 11.4.1.3. Spatial Resolution [3]
  - 11.4.1.4. Energy Resolution [3]
  - 11.4.1.5. Spatial Linearity [3]
  - 11.4.1.6. Sensitivity [3]
  - 11.4.1.7. Count-Rate Performance [3]
  - 11.4.1.8. Dead-Time [2]

Module Specific References

1. Cherry, S. A., Sorenson, J. A., & Phelps, M. E. (2012). *Physics in Nuclear Medicine* (4th ed.). Saunders Elsevier.
2. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
3. Mettler, F. A., & Guiberteau, M. J. (2018). *Essentials of Nuclear Medicine and Molecular Imaging* (7th ed.). Elsevier Health Sciences.
4. Naddaf, S. Y., Collier, B. D., Elgazzar, A. H., & Khalil, M. M. (2004). Technical errors in planar bone scanning. *Journal of nuclear medicine technology*, *32*(3), 148-153,
5. IAEA. (2003). *IAEA Quality Control Atlas for Scintillation Camera Systems*. International Atomic Energy Agency.
6. Prekeges, J. (2013). *Nuclear Medicine Instrumentation* (2nd ed.). Jones & Bartlett Learning.
7. Waterstram-Rich, K. M., & Gilmore, D. (2022). *Nuclear Medicine and PET/CT: Technology and Techniques* (9th ed.). Elsevier.
8. Zanzonico, P. (2008). Routine quality control of clinical nuclear medicine instrumentation: a brief review. *Journal of Nuclear Medicine*, *49*(7), 1114-1131,

Example Q&A:

Q1. (Effective Use) A single 20% energy window is set symmetrically on the 159 keV photopeak for an ^{123}I imaging study in a gamma camera. The lower and upper energy windows are:

A. 0 and 159 keV
B. 143 and 175 keV
C. 127 and 159 keV
D. 159 and 191 keV

Answer: B – 143 and 175 keV

Explanation: A symmetric 20% window would extend from 10% below the peak to 10% above the peak, i.e., 143 – 175 keV.

References:[1]Cherry. (2012) *Physics in Nuclear Medicine*

Q2. (Underlying Technology and Physical Principles) Which of the following devices/techniques is used to reject scattered photons on a scintillation camera?

A. Pulse height analyzer (PHA)
B. Time of Flight (TOF)
C. Collimator
D. Grid

Answer: A – Pulse height analyzer (PHA)

Explanation: Scattered photons have less energy, and the pulse height analyzer determines the energy deposited in the crystal and allows acceptance of photons with the proper energy range. TOF is used on PET scanners to partially locate events. A collimator is for the proper placement of photons related to a specific anatomic location. Grids are used on x-ray systems.

References:[1]Cherry. (2012) *Physics in Nuclear Medicine*

Q3. (Effective Use) What collimator should be used when imaging ^{111}In?

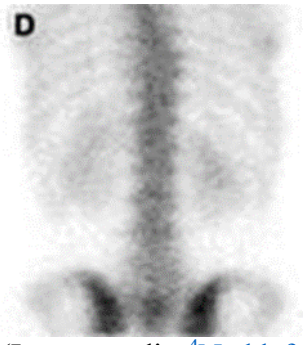
A. Low energy
B. Medium energy
C. High energy
D. Low energy High resolution

Answer: B – Medium energy

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Mettler & Guiberteau. (2018) *Essentials of Nuclear Medicine and Molecular Imaging*

Q4. (Effective Use) The following gamma camera bone image was collected with the camera head placed 30 cm from the body. If the patient were to be rescanned, what can be done to improve the spatial resolution of the image?



(Image credit: [4]Naddaf. (2004) *Technical errors in planar bone scanning*)

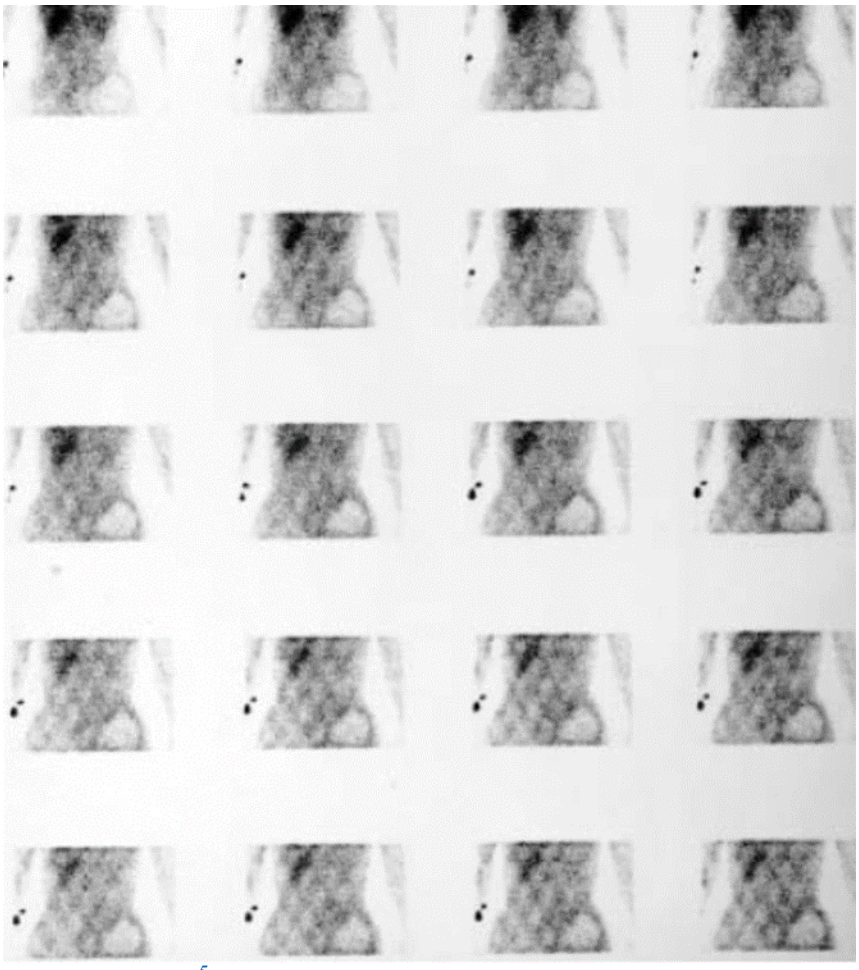
A. Increase the total number of counts
B. Use a larger pixel size
C. Move the camera closer to the patient
D. Applied a post-image smoothing filter

Answer: C – Move the camera closer to the patient

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

References:[4]Naddaf. (2004) *Technical errors in planar bone scanning*

Q5. (Image Characteristics and Artifacts) What can be determined from the image quality of the dynamic planar ^{99m}Tc-DTPA study of the kidneys?



(Image Credit: [5]IAEA. (2003) *IAEA Quality Control Atlas for Scintillation Camera Systems*)

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

Answer: B – Improperly tuned photomultiplier tubes

Explanation: The acquisition protocol that resulted in the artifact on the left side of the patient started with a static acquisition and transitioned to a continuous bed acquisition. An improperly tuned or damaged PMT is evident by the focal spot of concentrated counts.

References:[5]IAEA. (2003) *IAEA Quality Control Atlas for Scintillation Camera Systems*

Q6. (Underlying Technology and Physical Principles) What is the purpose of photomultiplier tubes (PMTs) in nuclear medicine instrumentation?

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

Answer: B – Convert visible light into an electrical signal

Explanation: PMT are constructed with a photocathode followed by a series of dynodes. The role of the photocathode is to convert light from crystal excitation to a proportionate number of electrons. Then the dynodes amply the signal by a factor of approximately 6 x 10^7 for a 10-stage PMT.

References: [1]Cherry. (2012) *Physics in Nuclear Medicine*; [6]Prekeges. (2013) *Nuclear Medicine Instrumentation*; [7]Waterstram-Rich & Gilmore. (2022) *Nuclear Medicine and PET/CT: Technology and Techniques*

Q7. (Safety, Quality Management, and Regulatory Issues) How often should evaluation of the radionuclide photopeak (peaking) be done?

A. Daily
B. Weekly
C. Quarterly
D. Annually

Answer: A – Daily

Explanation: The radionuclide should be checked daily, before any patients are scanned.

References: [3]Mettler & Guiberteau. (2018) *Essentials of Nuclear Medicine and Molecular Imaging*; [8]Zanzonico. (2008) *Routine quality control of clinical nuclear medicine instrumentation: a brief review*

Q8. (Safety, Quality Management, and Regulatory Issues) How often should the low count uniformity flood field be checked?

A. Daily
B. Weekly
C. Quarterly
D. Annually

Answer: A – Daily

Explanation: The low count uniformity flood field should be checked daily, before patients are scanned.

References:[3]Mettler & Guiberteau. (2018) *Essentials of Nuclear Medicine and Molecular Imaging*

MODULE 12: SINGLE PHOTON EMISSION COMPUTED TOMOGRAPHY (SPECT)

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

Fundamental Knowledge:

1. Describe the difference between planar NM imaging and SPECT.
2. Describe the major components and principles of operation of SPECT cameras.
3. Describe the types of data acquisition orbits (body-contour, circular).
4. Describe image reconstruction methods in SPECT.
5. Describe the application of attenuation correction in SPECT.

Clinical Applications and Problem Solving:

1. Discuss some of the most common SPECT exams including gated cardiac SPECT studies.
2. Discuss the effect of acquisition parameters on various characteristics of SPECT images.
3. Determine the indications and radiopharmaceutical activity administered to adults and pediatric patients for various SPECT exams.
4. Describe common image artifacts seen in SPECT.
5. Describe the key quality control (QC) tests for SPECT cameras.

Curriculum:

12. Single Photon Emission Computed Tomography (SPECT)
12.1. Underlying Technology and Physical Principles [3]
    12.1.1. Camera Components [3]
        12.1.1.1. Collimator [3]
        12.1.1.2. Camera Head [3]
        12.1.1.3. Scintillator / PMT [3]
    12.1.2. Electronics [3]
        12.1.2.1. Energy & Positioning Circuitry [3]
        12.1.2.2. Photopeak Window and Scatter Rejection [3]
    12.1.3. Image Acquisition [3]
        12.1.3.1. Body Contour and Circular Orbits [3]
        12.1.3.2. Matrix Size, Zoom [3]
        12.1.3.3. Number of Views [3]
        12.1.3.4. Acquisition Time (Time per Stop) [3]
        12.1.3.5. Acceptable Count Rate [2]
        12.1.3.6. Cardiac Gating [3]
        12.1.3.7. Respiratory Gating [1]
    12.1.4. Image Reconstruction [3]
        12.1.4.1. Sinograms [3]
        12.1.4.2. Filtered Back Projection (FBP) and Iterative Reconstruction (IR) [3]
            12.1.4.2.1. Effect of # Iterations and Subsets in IR [2]
            12.1.4.2.2. Filters (Ramp, Shepp-Logan, Hamming, Hann) [2]
        12.1.4.3. Resolution Recovery (PSF in Reconstruction) [2]
    12.1.5. Attenuation Correction (AC) [3]

12.1.5.1. Chang's Attenuation Correction [3]
12.1.5.2. CT Attenuation Correction [3]
12.1.5.3. Importance of AC in Cardiac Imaging [3]
12.2. Image Characteristics and Artifacts [3]
12.2.1. Spatial Resolution, Contrast Resolution, Noise [3]
12.2.2. Partial Volume Effect [3]
12.2.3. CNR & Lesion Detectability [3]
12.2.3.1. Effect of Lesion Size [3]
12.2.3.2. Effect of Background Count Rate [3]
12.2.4. Effect of Acquisition Parameters (Matrix Size, # of Angles, Time per Stop) [3]
12.2.5. Common Artifacts [3]
12.2.5.1. Camera Related (Collimator, PMT, Crystal, etc.) [3]
12.2.5.2. Co-registration Related (SPECT and CT) [3]
12.2.5.3. Patient Related (Motion, Attenuation, Contamination, etc.) [3]
12.3. Effective Use [3]
12.3.1. Common Imaging Exams [3]
12.3.1.1. Thyroid and Parathyroid [3]
12.3.1.2. Cardiac (Ejection Fraction, Myocardial Perfusion) [3]
12.3.1.3. Skeletal [3]
12.3.1.4. Brain (ECD, DATScan) [3]
12.3.1.5. Lung (V/Q) (Perfusion SPECT) [3]
12.3.1.6. Infection (^{111}In) [2]
12.3.2. Radiopharmaceutical Administered Activity [3]
12.3.2.1. Typical Adult and Pediatric Dosage [3]
12.3.2.2. SNMMI/EANM Consensus Guidelines - Pediatric Administered Activities [2]
12.4. Safety, Quality Management, & Regulatory Issues [3]
12.4.1. Specific SPECT QC [3]
12.4.1.1. Center-of-Rotation Calibration [3]
12.4.1.2. Imaging Performance Using Jaszczak Phantom (Cold Spheres, Uniformity and Spatial Resolution) [3]

Module Specific References

1. Abrahams, R. B., Huda, W., & Sensakovic, W. F. (2019). *Imaging Physics Case Review: Imaging Physics Case Review E-Book* (1st ed.). Elsevier Health Sciences.
2. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
3. Dorbala, S., et al. (2018). Single photon emission computed tomography (SPECT) myocardial perfusion imaging guidelines: instrumentation, acquisition, processing, and interpretation. *Journal of Nuclear Cardiology*, *25*(5), 1784-1846,
4. Cherry, S. A., Sorenson, J. A., & Phelps, M. E. (2012). *Physics in Nuclear Medicine* (4th ed.). Saunders Elsevier.
5. Mettler, F. A., & Guiberteau, M. J. (2018). *Essentials of Nuclear Medicine and Molecular Imaging* (7th ed.). Elsevier Health Sciences.
6. Iskandrian, A. E., & Hage, F. G. (2024). *Nuclear Cardiac Imaging: Principles and Applications* (6th ed.). Oxford University Press.

7. ACR. *American College of Radiology: Nuclear medicine accreditation program requirements*. American College of Radiology https://accreditationsupport.acr.org/support/solutions/11000003459

Example Q&A:

Q1. (Image Characteristics and Artifacts) Which imaging metric is improved the most in a SPECT imaging compared to planar nuclear medicine imaging?

A. Spatial resolution
B. Temporal resolution
C. Lesion contrast
D. Patient dose

Answer: C – Lesion contrast

Explanation: The principal improvement in SPECT images is the higher lesion contrast, which is achieved due to volumetric reconstruction and the consequent "removal" of the overlying and underlying tissue. The spatial resolution of the SPECT images is worse that planar images, and so is the temporal resolution since they take much longer to acquire than planar images. The patient dose (injected radiopharmaceutical activity) is very similar.

References:[1]Abrahams. (2019) *Imaging Physics Case Review: Imaging Physics Case Review E-Book*; [2]Bushberg. (2021) *The Essential Physics of Medical Imaging*

Q2. (Underlying Technology and Physical Principles) What is the typical number of views per camera head for a routine cardiac SPECT exam?

A. 64
B. 128
C. 256
D. 512

Answer: A – 64

Explanation: For a typical 2 headed SPECT camera, the American Society for Nuclear Cardiology (ASNC) recommends the number of views per head as 64, accompanied by a 128 x 128 matrix.

References:[3]Dorbala. (2018) *Single photon emission computed tomography (SPECT) myocardial perfusion imaging guidelines: instrumentation, acquisition, processing, and interpretation*

Q3. (Underlying Technology and Physical Principles) What is the principal benefit of using body-contour orbit instead of circular orbit in a SPECT acquisition?

A. Improved resolution
B. Higher contrast
C. Reduced mottle
D. Fewer artifacts

Answer: A – Improved resolution

Explanation: Spatial resolution in planar as well as SPECT studies reduces with increasing patient to camera head distance. While circular orbits will maintain a fixed distance from the center of rotation, body contour orbits allow the camera head to move in as close to the patient as possible, thus improving spatial resolution.

References:[1]Abrahams. (2019) *Imaging Physics Case Review: Imaging Physics Case Review E-Book*; [2]Bushberg. (2021) *The Essential Physics of Medical Imaging*

Q4. (Effective Use) Which collimator should be used when imaging ^{111}In?

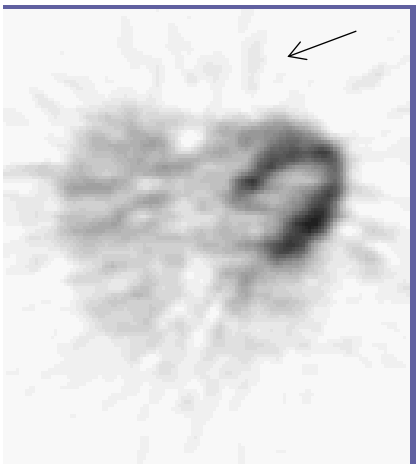
A. Low energy
B. Medium energy
C. High energy

Answer: B – Medium energy

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

References:[4]Cherry. (2012) *Physics in Nuclear Medicine*; [5]Mettler & Guiberteau. (2018) *Essentials of Nuclear Medicine and Molecular Imaging*

Q5. (Image Characteristics and Artifacts) What reconstruction algorithm causes the streaking artifact outside the body as indicated by the arrow in the cardiac perfusion image?



(Image courtesy of Jonathon A. Nye, PhD, Medical University of South Carolina)

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

Answer: A – Filtered backprojection

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

References:[4]Cherry. (2012) *Physics in Nuclear Medicine*

Q6. (Effective Use) What is the primary reason that 180° RAO-LPO instead of 360° acquisition orbits are used for cardiac SPECT?

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

Answer: B – Reduce attenuation

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

References:[6]Iskandrian & Hage. (2024) *Nuclear Cardiac Imaging: Principles and Applications*

Q7. (Safety, Quality Management, & Regulatory Issues) What is the ACR recommended frequency for a center-of-rotation test for a SPECT system?

A. Daily
B. Weekly
C. Monthly
D. Yearly

Answer: C – Monthly

Explanation: The ACR recommends that a center of rotation test be performed monthly for SPECT systems.

References:[7]ACR. *American College of Radiology: Nuclear medicine accreditation program requirements*

MODULE 13: POSITRON EMISSION TOMOGRAPHY (PET)

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

Fundamental Knowledge:

1. Describe the difference between SPECT and PET.
2. Describe the major components and principles of operation of PET cameras.
3. Describe the data acquisition in PET.
4. Describe the role of attenuation correction in PET imaging.
5. Describe the types of PET count rates (trues, randoms, scatter).
6. Describe image reconstruction methods in PET.

Clinical Applications and Problem Solving:

1. Discuss the importance of Specific Uptake Value.
2. Discuss some common PET exams.
3. Describe how the selection of image acquisition parameters affects image quality in PET images.
4. Determine the indications and radiopharmaceutical activity administered to adults and pediatric patients for various PET exams.
5. Describe common image artifacts seen in PET exams and the methods to minimize them.
6. Describe the key quality control tests for PET cameras.

Curriculum:

13. Positron Emission Tomography
13.1. Underlying Technology and Physical Principles [3]
    13.1.1. Camera Components [3]
        13.1.1.1. Detector Ring [3]
        13.1.1.2. Role of Septa (2D vs 3D) [2]
        13.1.1.3. Scintillators in PET [3]
    13.1.2. Electronics [3]
        13.1.2.1. Coincidence Timing Window [3]
        13.1.2.2. Energy & Positioning Circuitry [3]
        13.1.2.3. Random and Scatter Rejection [3]
    13.1.3. Image Acquisition [3]
        13.1.3.1. List-Mode Data Acquisition [3]
        13.1.3.2. Matrix Size [3]
        13.1.3.3. Acquisition Time (Time per Bed) [3]
        13.1.3.4. Count Rates (Trues, Randoms, Scatter) [3]
        13.1.3.5. Cardiac Gating [3]
        13.1.3.6. Respiratory Gating [2]
    13.1.4. Image Reconstruction [3]
        13.1.4.1. Lines of Response (LOR) [3]
        13.1.4.2. Sinograms [3]
        13.1.4.3. Iterative Reconstruction (IR) [3]
            13.1.4.3.1. Effect of Iterations and Subsets [2]

- 13.1.4.3.2. Advantages/Disadvantages of IR [2]
- 13.1.4.4. Resolution Recovery (PSF in Reconstruction) [2]
- 13.1.5. CT Attenuation Correction (CTAC) [3]
  - 13.1.5.1. Spatial Resolution - Down-Sampling of CT data [3]
  - 13.1.5.2. Energy - Bilinear Function Mapping μ_{120kV} (CT) to μ_{511keV} (PET) [3]
  - 13.1.5.3. Importance of AC in Cardiac Imaging [3]
- 13.1.6. Time of Flight PET [3]

13.2. Image Characteristics & Artifacts [3]
- 13.2.1. Spatial Resolution, Contrast, Noise [3]
- 13.2.2. Partial Volume Effect [3]
- 13.2.3. CNR & Lesion Detectability [3]
  - 13.2.3.1. Effect of Lesion Size [3]
  - 13.2.3.2. Effect of Background Count Rate [3]
- 13.2.4. Standard Uptake Value (SUV) [3]
  - 13.2.4.1. Definition [3]
  - 13.2.4.2. Types of SUV – SUV_{bw}, Lean-Body Mass SUV_{lbm} and Body Surface-Area SUV_{bsa} [2]
- 13.2.5. Factors Affecting SUV (Patient Preparation, Uptake Time, etc.) [3]
- 13.2.6. Advantage of TOF and PSF in PET [3]
- 13.2.7. Common Artifacts
  - 13.2.7.1. Camera Related (Collimator, PMT, Crystal, etc.)
  - 13.2.7.2. Reconstruction Related (e.g., High Activity "Rim" Due to CT Truncation) [2]
  - 13.2.7.3. Patient Related (Motion, Metal, Iodine Contrast, Respiratory, Contamination, etc.) [3]

13.3. Effective Use [3]
- 13.3.1. Common Imaging Exams [3]
  - 13.3.1.1. Oncology (Lung, Liver, Colorectal, Brain, Head & Neck, etc.) [3]
  - 13.3.1.2. Cardiac (Ejection Fraction, Myocardial Perfusion) [2]
  - 13.3.1.3. Brain Disorders (Alzheimer's, Dementia, etc.) [3]
- 13.3.2. Radiopharmaceuticals Administered Activity [3]
  - 13.3.2.1. Typical Adult and Pediatric Dosage [3]

13.4. Safety, Quality Management, & Regulatory Issues [3]
- 13.4.1. PET QC [3]
  - 13.4.1.1. Daily QC [3]
  - 13.4.1.2. Normalization and Well-counter Correction [2]
  - 13.4.1.3. ACR Tests for Imaging Performance Using Jaszczak Phantom with Esser Lid (Hot Cylinders, Uniformity, Spatial Resolution, SUV Ratios) [2]

Module Specific References

1. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
2. Mettler, F. A., & Guiberteau, M. J. (2018). *Essentials of Nuclear Medicine and Molecular Imaging* (7th ed.). Elsevier Health Sciences.
3. Pan, T., et al. (2005). Attenuation correction of PET images with respiration-averaged CT images in PET/CT. *Journal of Nuclear Medicine*, *46*(9), 1481-1487,

4. Truong, M. T., Pan, T., & Erasmus, J. J. (2006). Pitfalls in integrated CT-PET of the thorax: implications in oncologic imaging. *Journal of Thoracic Imaging*, *21*(2), 111-122,
5. Mattsson, S., et al. (2015). ICRP publication 128: radiation dose to patients from radiopharmaceuticals: a compendium of current information related to frequently used substances. *Annals of the ICRP*, *44*(2_suppl), 7-321,
6. Cherry, S. A., Sorenson, J. A., & Phelps, M. E. (2012). *Physics in Nuclear Medicine* (4th ed.). Saunders Elsevier.

Example Q&A:

Q1. (Effective Use) An incorrect patient weight of 100 kg greater than the true weight is entered during a PET exam. What effect will this have on the Standard Uptake Value (SUV) reported by the scanner?

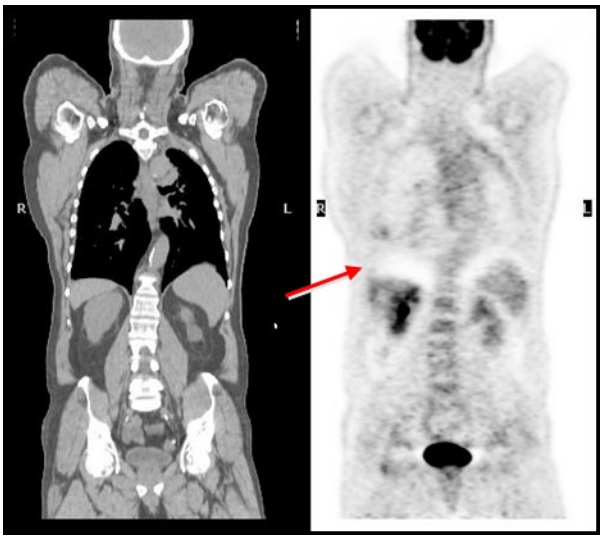
A. Reported SUV value is correct
B. Reported SUV value greater than the correct SUV value
C. Reported SUV value less than the correct SUV value

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

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Mettler & Guiberteau. (2018) *Essentials of Nuclear Medicine and Molecular Imaging*

Q2. (Image Characteristics and Artifacts) What is the cause of the photopenic area at the diaphragm–lung interface of the right image compared to the left FDG PET/CT coronal image?



(Image courtesy of Tinsu Pan, PhD, MD Anderson Cancer Center)

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

Answer: B – Respiratory motion misregistration

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

References:[3]Pan. (2005) *Attenuation correction of PET images with respiration-averaged CT images in PET/CT*; [4]Truong. (2006) *Pitfalls in integrated CT-PET of the thorax: implications in oncologic imaging*

Q3. (Image Characteristics and Artifacts) On what is the system resolution of a PET camera principally dependent?

A. Size of the detector element
B. Decay time of the scintillator
C. Presence or absence of septa
D. Diameter of the detector ring

Answer: A – Size of the detector element

Explanation: : PET cameras do not use a collimator for image formation like SPECT cameras. The image formation is accomplished with lines of response formed by coincidence detection of 511 keV gamma photons. PET camera detectors consist of pixelated rings of scintillators. The single biggest factor that determines the spatial resolution in PET imaging is the size of the pixel, i.e. the detector element.

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*

Q4. (Effective Use) What is the patient organ receiving the maximum radiation dose during a routine oncologic FDG PET scan?

A. Liver
B. Brain
C. Heart wall
D. Bladder wall

Answer: D – Bladder wall

Explanation: The ^{18}F-FDG that is cleared by the kidneys accumulates in the urinary bladder.

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [5]Mattsson. (2015) *ICRP publication 128: radiation dose to patients from radiopharmaceuticals: a compendium of current information related to frequently used substances*

Q5. (Underlying Technology and Physical Principles) Which of the following scintillators is optimal for time-of-flight (TOF) PET imaging?

A. GSO
B. BGO
C. LSO
D. CsI

Answer: C – LSO

Explanation: The fast decay time of 40 ns and a good light output makes LSO the scintillator of choice for TOF imaging.

References:[6]Cherry. (2012) *Physics in Nuclear Medicine*

Q6. (Underlying Technology and Physical Principles) What is the approximate typical coincidence timing window for modern PET scanners?

A. 6 s
B. 6 ms
C. 6 ns
D. 6 ps

Answer: C – 6 ns

Explanation: Most modern PET scanners have a coincidence timing window between 6 to 12 ns.

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [6]Cherry. (2012) *Physics in Nuclear Medicine*

Q7. (Safety, Quality Management, & Regulatory Issues) Which is the PET quality control test done to ensure a uniform response of all the detectors in a PET gantry?

A. Well-counter correction
B. Attenuation correction
C. Scatter correction
D. Normalization correction

Answer: D – Normalization correction

Explanation: PET cameras consist of tens of thousands of individual detectors which have slightly different responses, leading to differences in number of detected events along a given line of response (LOR). A normalization scan corrects for this. It is done by exposing all the detectors to a uniform source of activity. Ideally, each LOR should record the same number of detected events, and any difference is due to individual variations of the detectors. This difference is converted into a "normalization factor" for each LOR and is applied to clinical data to yield the correct quantitation.

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*

MODULE 14: HYBRID IMAGING AND NUCLEAR MEDICINE THERAPY

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

Fundamental Knowledge:

1. Describe the rationale behind hybrid imaging.
2. Compare the relative advantages of hybrid imaging (SPECT/CT; PET/CT; PET/MR).
3. Describe the major components and principles of operation of PET/MR cameras.
4. Role of alphas, betas and gammas in therapeutic nuclear medicine.

Clinical Applications and Problem Solving:

1. Describe some common SPECT/CT, PET/CT and PET/ MR exams.
2. Describe some common radiopharmaceuticals used in therapeutic nuclear medicine.
3. Emerging role of theranostics.

Curriculum:

14. Hybrid Imaging and Nuclear Medicine Therapy
14.1. Underlying Technology and Physical Principles [3]
    14.1.1. Rationale for Hybrid Imaging [3]
        14.1.1.1. Advantages of SPECT/CT Over SPECT; PET/CT Over PET [3]
        14.1.1.2. Advantages/Disadvantages of PET/MR [3]
        14.1.1.3. PET/MR Cameras [3]
            14.1.1.3.1. Components of PET/ MR Camera [3]
            14.1.1.3.2. Role of SiPM and APDs in PET/MR [2]
            14.1.1.3.3. Attenuation Correction in PET/MR [2]
    14.1.2. Therapeutic Nuclear Medicine [3]
        14.1.2.1. Role of Alpha and Beta Emissions in Therapy [3]
        14.1.2.2. Range of Alpha and Beta Particles in Tissue [3]
        14.1.2.3. Theranostics [3]
14.2. Image Characteristics and Artifacts (Refer to Module 13) [3]
14.3. Effective Use [3]
    14.3.1. Clinical Applications of Hybrid Imaging [3]
        14.3.1.1. Common Imaging Exams [3]
            14.3.1.1.1. SPECT/CT [3.0]
            14.3.1.1.2. PET/CT [3]
            14.3.1.1.3. PET/MR [2]
    14.3.2. Clinical Applications of Therapeutic Nuclear Medicine [3]
        14.3.2.1. Radioiodine Therapy [3]
            14.3.2.1.1. Role of Imaging with ^{123}I Before NaI Therapy
            14.3.2.1.2. ^{131}I-NaI Doses for Hyperthyroid Treatment & Ablation [3]
            14.3.2.1.3. ^{131}I-mIBG [2]
    14.3.3. Clinical Theranostics [3]
        14.3.3.1. ^{90}Y Therapy [3]
        14.3.3.2. ^{223}Ra Therapy [3]

14.3.3.3. ^{177}Lu Therapy (NETs) [3]
14.3.3.4. ^{177}Lu Therapy (PSMA) [3]
14.4. Safety, Quality Management and Regulatory Issues (Refer to Module 15) [3]

Module Specific References

1. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
2. Mettler, F. A., & Guiberteau, M. J. (2018). *Essentials of Nuclear Medicine and Molecular Imaging* (7th ed.). Elsevier Health Sciences.
3. Cherry, S. A., Sorenson, J. A., & Phelps, M. E. (2012). *Physics in Nuclear Medicine* (4th ed.). Saunders Elsevier.

Example Q&A:

Q1. (Image Characteristics and Artifacts) What is the main advantage of using CT for attenuation correction in a SPECT/CT or a PET/CT system?

A. Quicker attenuation scans
B. Less statistical noise in SPECT/ PET data
C. Higher spatial resolution attenuation data
D. All of the above

Answer: D – All of the above

Explanation: Replacing the radioactive attenuation correction source with CT has all the listed advantages. The attenuation correction scans with a radioactive source take several minutes compared to CT, which can be accomplished within seconds. Moreover, due to the high flux of the CT x-ray source, the statistical noise in suppressed. Lastly CT images provide a very high spatial resolution, allowing for a more accurate attenuation correction map.

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Mettler & Guiberteau. (2018) *Essentials of Nuclear Medicine and Molecular Imaging*

Q2. (Underlying Technology and Physical Principles) What is the main advantage of replacing PMTs with SiPMs in modern PET/MR systems?

A. Cost-effectiveness of SiPMs
B. SiPMs are not affected by the MRI magnetic field
C. SiPMs have a lesser dark-noise than PMTs

Answer: B – SiPMs are not affected by the MRI magnetic field

Explanation: SiPMs are also more expensive to manufacture than PMTs. The dark-noise in PMTs is actually lower than in SiPMs. The principal advantage of using SiPMs is that unlike PMTs, they are not affected by the static magnetic field (B_0) from the MR scanner.

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*

Q3. (Effective Use) Why is a beta emitting radioisotope used for localized therapy instead of a gamma emitting radioisotope?

A. Beta radioisotopes are cheaper
B. Beta range in tissue is larger compared to gammas
C. Betas range in tissue is smaller compared to gammas

Answer: C - Betas range in tissue is smaller compared to gammas

Explanation: Betas have a very short range in tissue (of the order of ≤ 1 mm). Gammas can penetrate several centimeters or tens of centimeters of tissue. Thus, for localized energy deposition and dose delivery, beta emitting radioisotopes are the right choice, while gamma emitting radioisotopes are used for imaging.

References:[3]Cherry. (2012) *Physics in Nuclear Medicine*

MODULE 15: BIOLOGICAL EFFECTS OF IONIZING RADIATION

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

Fundamental Knowledge:

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

Clinical Applications and Problem Solving:

1. Understand the risks to patients from high-dose fluoroscopy regarding tissue reactions (deterministic effects) and the importance of applying radiation protection principles.
2. Counsel a pregnant woman on the potential radiation risks to the fetus.
3. Recognize the benefit vs. risk in radiation uses and recognize the information sources that can be used to assist in assessing this ratio.

Curriculum:

15. Radiation Biology
15.1. Principles [3]
    15.1.1. Linear Energy Transfer (LET) [2]
    15.1.2. Relative Biological Effectiveness (RBE) [3]
    15.1.3. Radiation Weighting Factors [3]
    15.1.4. Tissue Weighting Factors [3]
15.2. Molecular Effects of Radiation [3]
    15.2.1. Direct vs. Indirect Effects [3]
    15.2.2. Effects of Radiation on DNA [2]
15.3. Cellular Effects of Radiation [2]
    15.3.1. Law of Bergonié and Tribondeau [2]
    15.3.2. Radiosensitivity of Different Cell Types [3]
    15.3.3. Cell Cycle Radiosensitivity [2]
    15.3.4. Cell Damage, Survival, Repair, and Death [2]
    15.3.5. Dose Fractionation [2]
15.4. Systemic Effects of Radiation [3]
    15.4.1. Tissue and Organs [3]
    15.4.2. Whole Body [3]
    15.4.3. Population (Age and Gender) [3]

15.5. Tissue Reactions (Deterministic) Effects [3]
- 15.5.1. Acute Radiation Syndromes [2]
  - 15.5.1.1. Sequence of Events [2]
  - 15.5.1.2. Hematopoietic [2]
  - 15.5.1.3. Gastrointestinal [2]
  - 15.5.1.4. Neurovascular [2]
  - 15.5.1.5. $LD_{50/60}$ [2]
  - 15.5.1.6. Monitoring and Intervention [2]
- 15.5.2. Skin Effects [3]
- 15.5.3. Lens Effects [3]
- 15.5.4. Reproductive Impact [3]

15.6. Stochastic Radiation Effects [3]
- 15.6.1. Carcinogenesis [3]
  - 15.6.1.1. Radiation-Induced Cancers [3]
    - 15.6.1.1.1. Leukemia [3]
    - 15.6.1.1.2. Solid Tumors [3]
  - 15.6.1.2. Spontaneous Rate (Natural Incidence) [3]
  - 15.6.1.3. Latency [3]
- 15.6.2. Mutagenesis [2]

15.7. Teratogenesis [3]
- 15.7.1. Developmental Effects [3]
- 15.7.2. Childhood Leukemia [3]
- 15.7.3. Gestational Sensitivity [3]

15.8. Radiation Risk [3]

15.9. Benefit vs. Risk in Radiology [3]

15.10. Definition and Communication of Risk (e.g., relative, absolute, etc.) [3]

15.11. Dose-Response Models [3]
- 15.11.1. Linear No-Threshold (LNT) [3]
- 15.11.2. Linear-Quadratic [2]
- 15.11.3. Radiation Hormesis/Adaptive Response [2]
- 15.11.4. Bystander Effect [2]

Module Specific References

1. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
2. Hall, E. J., & Giaccia, A. J. (2018). *Radiobiology for the Radiologist* (8th ed.). Lippincott Williams and Wilkins.
3. NRCNA. (2006). *Health risks from exposure to low levels of ionizing radiation: BEIR VII phase 2*. The National Academies Press.
4. United Nations Scientific Committee on the Effects of Atomic Radiation. (2014). *Sources, Effects and Risks of Ionizing Radiation - UNSCEAR 2013 Report*. United Nations.
5. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.

Example Q&A:

Q1. Which of the following has the highest LET?

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

Answer: A – Alpha particle

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Hall & Giaccia. (2018) *Radiobiology for the Radiologist*

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

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

Answer: D – M phase

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Hall & Giaccia. (2018) *Radiobiology for the Radiologist*

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

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

Answer: A – Deoxyribonucleic acid

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Hall & Giaccia. (2018) *Radiobiology for the Radiologist*

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

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

Answer: D – Carcinogenesis

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Hall & Giaccia. (2018) *Radiobiology for the Radiologist*

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

A. 3-5 mGy
B. 30-50 mGy
C. 300-500 mGy
D. 3000-5000 mGy

Answer: D –3000-5000 mGy

Explanation: The $LD_{50/60}$ for humans is approximately 3500 mGy-4000 mGy. Lethal dose 50/60 is the dose of radiation to the whole body that causes 50% of irradiated subjects to die within 60 days without medical intervention.

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Hall & Giaccia. (2018) *Radiobiology for the Radiologist*

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

A. Fetal malformation
B. Prenatal death
C. Leukemia
D. Cataracts

Answer: C – Leukemia

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Hall & Giaccia. (2018) *Radiobiology for the Radiologist*

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

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

Answer: A – Breast

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Hall & Giaccia. (2018) *Radiobiology for the Radiologist*

Q8. What is the stochastic dose response model that forms the basis of radiation protection regulations in the US?

A. Linear-Quadratic
B. Linear Threshold
C. Linear No-Threshold
D. Radiation Hormesis

Answer: C – Linear No-Threshold

Explanation: In the US, radiation protection regulations are based on the Linear No-Threshold model which is used for solid tumor response. The Linear-Quadratic model is used for leukemia response.

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]NRCNA. (2006) *Health risks from exposure to low levels of ionizing radiation: BEIR VII phase 2*; [4]United Nations Scientific Committee on the Effects of Atomic Radiation. (2014) *Sources, Effects and Risks of Ionizing Radiation - UNSCEAR 2013 Report*

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

3 Gy	Hematopoetic Syndrome
12 Gy	Neurovascular Syndrome
50 Gy	Gastrointestinal Syndrome

Answer: 3 Gy = Hematopoetic Syndrome, 12 Gy = Gastrointestinal Syndrome, 50 Gy = Neurovascular Syndrome

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Hall & Giaccia. (2018) *Radiobiology for the Radiologist*; [3]NRCNA. (2006) *Health risks from exposure to low levels of ionizing radiation: BEIR VII phase 2*

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

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

Answer: D – 200 mSv

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [5]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

MODULE 16: RADIATION SAFETY

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

Fundamental Knowledge:

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

Clinical Applications and Problem Solving:

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

Curriculum:

16. Radiation Safety

16.1. Sources of Radiation Exposure [3]

- 16.1.1. Natural Background [3]
- 16.1.2. Medical Dose to Patients [3]
- 16.1.3. Consumer, Industrial, Security, Medical, Educational, and Research [1]

16.2. Occupational Dose [3]

- 16.2.1. X-ray Modalities [3]

16.7.2.2. Storage (Shielding of Gammas, Betas) [2]
16.7.2.3. Labeling and Logs [3]
16.7.3. Contamination Control (e.g. Protective Clothing, Chucks, etc.) [3]
16.7.4. Radioactive Waste Management / Hot Storage [3]
16.7.5. Definition of Authorized User [3]
16.7.5.1. Diagnostic Authorized User (10 CFR 35.200 and 35.100, or Equivalent Agreement State Regulations) [2]
16.7.5.2. Therapeutic Authorized User (10 CFR 35.300 and 35.1000, or Equivalent Agreement State Regulations) [2]
16.7.6. Role of Radiation Safety Officer and Radiation Safety Committee [3]
16.7.7. Medical Events [3]
16.7.7.1. Reporting and Follow-up [2]
16.7.7.2. Person or Agency to Receive Report [1]
16.7.8. Special Considerations [2]
16.7.8.1. Pregnant Patients [3]
16.7.8.2. Breast-Feeding Patients [3]
16.7.8.3. Caregivers [3]
16.7.8.4. Written Instructions [3]
16.7.9. Nuclear Medicine Theranostics/Therapy Safety [3]
16.7.9.1. Regulatory Considerations [2]
16.7.9.2. Clinical Utilization [2]
16.7.9.3. Written Directive [3]
16.7.9.4. Patient Safety and Release Considerations [3]
16.8. Radiological Emergencies [1]
16.8.1. Triage: Evaluation, Dispensation, and Initial Treatment [1]
16.9. Roles of Advisory Bodies [2]
16.9.1. International Commission on Radiological Protection (ICRP) [2]
16.9.2. United Nations Scientific Committee and the Effect of Atomic Radiation (UNSCEAR) [2]
16.9.3. National Council on Radiation Protection and Measurements (NCRP) [2]
16.9.4. Conference of Radiation Control Program Directors (CRCPD) [1]
16.9.5. International Atomic Energy Agency (IAEA) [2]
16.9.6. American College of Radiology (ACR) [2]
16.9.7. American Association of Physicists in Medicine (AAPM) [2]
16.9.8. National Electrical Manufacturers Association (NEMA) (Medical Imaging and Technology Alliance or MITA) [1]
16.9.9. International Commission on Radiation Units (ICRU) [1]
16.10. Roles of Regulatory Agencies [3]
16.10.1. U.S. Nuclear Regulatory Commission (NRC) and Agreement States [3]
16.10.2. The Joint Commission (TJC) [3]
16.10.3. State Agencies [1]
16.10.4. U.S. Food and Drug Administration (FDA) [2]
16.10.5. U.S. Office of Human Research Protections (OHRP) [1]
16.10.6. U.S. Department of Transportation (DOT) [2]
16.10.7. U.S. Environmental Protection Agency (EPA) [1]
16.10.8. U.S. Department of Labor (OSHA) [1]

16.10.9. International Electro-Technical Commission (IEC) [1]

Module Specific References

1. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
2. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.
3. NCRP. (1987). *NCRP Report No. 93 - Ionizing Radiation Exposure of the Population of the United States*. National Council of Radiation Protection and Measurements.
4. NCRP. (2019). *NCRP Report No. 184 – Medical Radiation Exposure of Patients in the United States*. National Council of Radiation Protection and Measurements.
5. CDC Radiation Studies Branch. (2014). *Population Monitoring in Radiation Emergencies: A Guide for State and Local Public Health Planners* (2nd ed.). Centers for Disease Control and Prevention.
6. 10 CFR 35.3045 - Report and notification of a medical event, (2005).
7. 10 CFR 35.2092 - Records of decay-in-storage, (2014).
8. 10 CFR 35.75 - Release of individuals containing unsealed byproduct material or implants containing byproduct material, (2007).

Example Q&A:

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

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

Answer: B – 50 mSv

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q2. By what factor has the yearly natural background radiation received per capita changed over time (NCRP Reports 93 (1987) and 184 (2019))?

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:[3]NCRP. (1987) *NCRP Report No. 93 - Ionizing Radiation Exposure of the Population of the United States*; [4]NCRP. (2019) *NCRP Report No. 184 – Medical Radiation Exposure of Patients in the United States*

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

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

Answer: C – 50%

Explanation: The total contribution from medical sources is approximately 3.0 mSv per capita per year in NCRP Report 184 (2019), a six-fold increase from 0.5 mSv per year. The total from all sources is approximately 6.2 mSv.

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]NCRP. (1987) *NCRP Report No. 93 - Ionizing Radiation Exposure of the Population of the United States*; [4]NCRP. (2019) *NCRP Report No. 184 – Medical Radiation Exposure of Patients in the United States*

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

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

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

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

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q5. As reported in NRCP Report 184, which category contributes the highest percentage to the total annual dose per capita?

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

Answer: D – Medical

Explanation: Medical includes the sum of the computed tomography (1.46 mSv per year), interventional fluoroscopy (0.43 mSv per year), conventional rad/fluoro (0.3 mSv per year), and nuclear medicine (0.80 mSv per year) contributions to the total annual dose per capita. Medical contributes 3.0 mSv per year, whereas radon's contribution is about 2.3 mSv per year. Therefore, the medical category is the highest percentage of the total. Cosmic radiation only contributes roughly 0.34 mSv per year.

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]NCRP. (1987) *NCRP Report No. 93 - Ionizing Radiation Exposure of the Population of the United States*; [4]NCRP. (2019) *NCRP Report No. 184 – Medical Radiation Exposure of Patients in the United States*

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

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

Answer: D – Optically stimulated luminescence (OSL) dosimeter

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: C – Respond and treat the injury

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [5]CDC Radiation Studies Branch. (2014) *Population Monitoring in Radiation Emergencies: A Guide for State and Local Public Health Planners*

Q8. Which of the following constitutes a medical event?

A. 5 mCi of ^{99m}Tc-sulfur colloid to the wrong patient
B. 0.3 mCi of ^{131}I-NaI rather than 0.3 mCi ^{123}I-NaI for uptake on a hyperthyroid patient
C. 30 mCi rather than the standard 8 mCi of ^{99m}Tc-sestamibi for a cardiac study
D. 20 mCi of ^{99m}Tc-sestamibi (cardiac agent) rather than 20 mCi of ^{99m}Tc-MDP (bone agent) to the correct patient

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

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

References:[6]*10 CFR 35.3045 - Report and notification of a medical event*. (2005) *10 CFR 35.3045 - Report and notification of a medical event*

Q9. For which of the following studies is more than a 24-hour interruption in breastfeeding recommended?

A. 10 mCi ^{18}F-FDG
B. 4 mCi ^{99m}Tc-Pertechnetate
C. 20 mCi ^{83}Rb-Chloride
D. 0.5 mCi ^{111}In White Blood Cells

Answer: D – 0.5 mCi ^{111}In White Blood Cells

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

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

Answer: C – Geiger–Müller Survey Meter

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q11. Which of the following may be held for decay in storage until background levels are obtained?

A. ^{57}Co marker source
B. ^{137}Cs reference source for well counter
C. ^{153}Gd transmission rod
D. ^{125}I seed for breast localization

Answer: D – ^{125}I seed for breast localization

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [7]*10 CFR 35.2092 - Records of decay-in-storage*. (2014) *10 CFR 35.2092 - Records of decay-in-storage*

Q12. To authorize the release of a patient treated with a therapeutic dosage of radioactive material, the dose to the most likely exposed individual must be less than what value?

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

Answer: D – 5 mSv

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

References: [8]*10 CFR 35.75 - Release of individuals containing unsealed byproduct material or implants containing byproduct material*. (2007) *10 CFR 35.75 - Release of individuals containing unsealed byproduct material or implants containing byproduct material*

MODULE 17: INFORMATICS

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

Fundamental Knowledge:

1. Understand basic concepts of image archiving / PACS.
2. Understand the relationship between the medical imaging industry standards (e.g. IHE, HL7, DICOM)
3. Understand the DICOM standard.

Clinical Applications and Problem Solving:

1. Describe the lifecycle of a Radiology Exam.
2. Describe the common equipment used for imaging informatics projects.

Curriculum:

17. Informatics
17.1. Basic Computer Terminology [3]
    17.1.1. Bits/Bytes, Bit Depth, Memory/HD space, CPU, GPU, etc. [3]
    17.1.2. Typical Image Matrix Size and Bit Depth [2]
17.2. Lifecycle of a Radiology Exam [3]
    17.2.1. Order Entry, scheduling, modalities, protocoling, exams, dictation, reporting, billing [3]
17.3. Integrating the Healthcare Enterprise (IHE), Health Level 7 (HL7), and DICOM [3]
    17.3.1. Importance of Standards [3]
    17.3.2. DICOM structured report (e.g. RDSR Radiation Dose Structured Report) [3]
    17.3.3. DICOM Header structure [3]
17.4. Picture Archiving and Communications System (PACS) [3]
    17.4.1. Medical Image Management and Processing System (MIMPS) [3]
    17.4.2. Local, Enterprise, Cloud Archiving [1]
    17.4.3. PACS Architectures [1]
        17.4.3.1. Vendor-Neutral Archiving (VNA) [1]
17.5. Definition of Radiology Information System (RIS) / Hospital Information System (HIS) and Electronic Medical Record (EMR) [3]
17.6. Storage [2]
    17.6.1. Storage Requirements and Disaster Recovery [2]
    17.6.2. Lossy vs Lossless Data Compression [2]
17.7. Security and Privacy [2]
    17.7.1. Anonymization, Encryption, and Firewalls [1]
    17.7.2. Research, Health Insurance Portability and Accountability (HIPAA), and Institutional Review Boards (IRB) [1]
17.8. Reporting [1]
    17.8.1. Dictation structure and templating [1]
    17.8.2. Natural language processing (NLP) [1]
    17.8.3. Annotation and image markup [1]
17.9. Decision Support [1]

17.9.1. Quality Cost Delivery Moral and Safety (qCDMS), Content Management System, & Appropriate Use Criteria [1]
17.10. Peer review systems (e.g. RADpeer) [1]
17.11. Critical/urgent results communication [1]
17.12. Discordant findings notification [1]
17.13. Standard Ontologies (e.g., ICD, CPT, SNOMED, RADLEX, LOINC, etc.) [1]
17.14. Environmental Design for View and Interpreting Images [2]
17.14.1. Environmental factors (monitor backlighting, fixed viewing conditions, etc.) [2]
17.14.2. Room layout (e.g., spacing and orientation of monitors) [2]
17.14.3. Hanging protocols [2]

Module Specific References

1. HL7-Health Level 7. (2024). *About HL7*. HL7. https://www.hl7.org/about/index.cfm?ref=nav
2. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
3. Huang, H. K. (2019). *PACS-Based Multimedia Imaging Informatics: Basic Principles and Applications* (3rd ed.). Wiley-Blackwell.

Example Q&A:

Q1. Which of the following is the standard for electronic data exchange in healthcare environments with special emphasis on inpatient acute care facilities (i.e. hospitals)?

A. ASCII
B. HL7
C. SMPTE
D. HIS

Answer: B – HL7

Explanation: Health Level 7 (HL7) develops standards for data exchange in medicine.

References:[1]HL7-Health Level 7. (2024) *About HL7*; [2]Bushberg. (2021) *The Essential Physics of Medical Imaging*

Q2. What is the file size of an MRI head study which has 64 slices and an image matrix size of 128 x 128 pixels with 16 bits per pixel?

A. 1 MB
B. 2 MB
C. 8 MB
D. 16 MB

Answer: B – 2 MB

Explanation: File Size (in bytes) = (height x width x bit depth)/8
For 64 slices: File Size = 64 x (128 x 128 x 16)/8 = 2 x 1024 x1024 bytes = 2 x 1024 kB = 2 MB.

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Huang. (2019) *PACS-Based Multimedia Imaging Informatics: Basic Principles and Applications*

Q3. What does PACS stand for in the context of radiology informatics?

A. Patient Access Control System
B. Picture Archiving and Communication System
C. Personalized Analysis and Clinical System
D. Primary Artifact Collection Software

Answer: B – Picture Archiving and Communication System

Explanation: PACS stands for Picture Archiving and Communication System, a technology that is used to acquire, store, and distribute medical images in digital form. It's an essential component of radiology informatics.

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Huang. (2019) *PACS-Based Multimedia Imaging Informatics: Basic Principles and Applications*

Q4. What is a primary objective of radiology informatics in the context of managing medical images??

A. Increasing image quality
B. Reducing radiology workload
C. Enhancing the security of patient data
D. Improving the storage and retrieval of medical images

Answer: D. Improving the storage and retrieval of medical images

Explanation: Radiology informatics aims to improve the efficiency and effectiveness of managing and accessing medical images.

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Huang. (2019) *PACS-Based Multimedia Imaging Informatics: Basic Principles and Applications*

Q5. In radiology informatics, what is the purpose of an RIS?

A. To control patient appointments
B. To enhance image quality
C. To manage radiation dose
D. To store digital images

Answer: A – To control patient appointments

Explanation: A Radiology Information System (RIS) is primarily used to manage and schedule patient appointments, track patient information, and manage the administrative and business aspects of radiology practices.

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Huang. (2019) *PACS-Based Multimedia Imaging Informatics: Basic Principles and Applications*

Q6. How do radiology informatics systems enhance diagnostic accuracy?

A. By administering treatment plans
B. By automating the radiologist's work
C. By providing access to historical patient data and images
D. By reducing the need for radiologic training

Answer: C – By providing access to historical patient data and images

Explanation: Radiology informatics systems play a crucial role in improving diagnostic accuracy by providing access to historical patient data and images. When radiologists have easy access to a patient's prior imaging studies and medical history, they can make more informed and accurate diagnoses. This historical context helps in comparing current images with previous ones, identifying changes, and making more precise assessments, ultimately leading to better patient care.

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Huang. (2019) *PACS-Based Multimedia Imaging Informatics: Basic Principles and Applications*

Q7. What is the primary purpose of a DICOM (Digital Imaging and Communications in Medicine) standard in radiology informatics?

A. To provide a standard for medical billing
B. To ensure interoperability of medical imaging equipment
C. To track radiation dose
D. To encrypt patient data

Answer: B – To ensure interoperability of medical imaging equipment

Explanation: The primary purpose of the DICOM standard in radiology informatics is to ensure interoperability of medical imaging equipment. DICOM is a widely adopted standard that facilitates the consistent exchange of medical images and information between different types of imaging devices, making it easier for healthcare providers to work with various equipment from different manufacturers.

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Huang. (2019) *PACS-Based Multimedia Imaging Informatics: Basic Principles and Applications*

Q8. What is a common issue encountered in radiology informatics?

A. Inaccurate patient identification
B. Limited integration with electronic health records
C. Decreased image quality
D. Managing large volumes of digital data

Answer: D – Managing large volumes of digital data

Explanation: Within radiology informatics, managing the substantial amount of digital data generated by various imaging modalities is a common challenge. It involves the secure storage, efficient retrieval, and proper archiving of these digital medical images. While the other options may be challenges in healthcare settings, managing digital data is particularly relevant to radiology informatics.

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Huang. (2019) *PACS-Based Multimedia Imaging Informatics: Basic Principles and Applications*

MODULE 18: IMAGE METRICS AND VIEWING

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

Fundamental Knowledge:

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

Clinical Applications and Problem Solving:

1. Assess the validity of the type of statistical analysis used in the radiology literature.
2. Evaluate how display, ambient lighting, and luminance affect reader performance.
3. Understand display quality control.
4. Know how to set up a quality improvement study.
5. Use ROC analysis to compare system performance.
6. Describe image quality differences between radiologist workstations and acquisition workstations.
7. Compare commercial vs medical grade displays.

Curriculum:

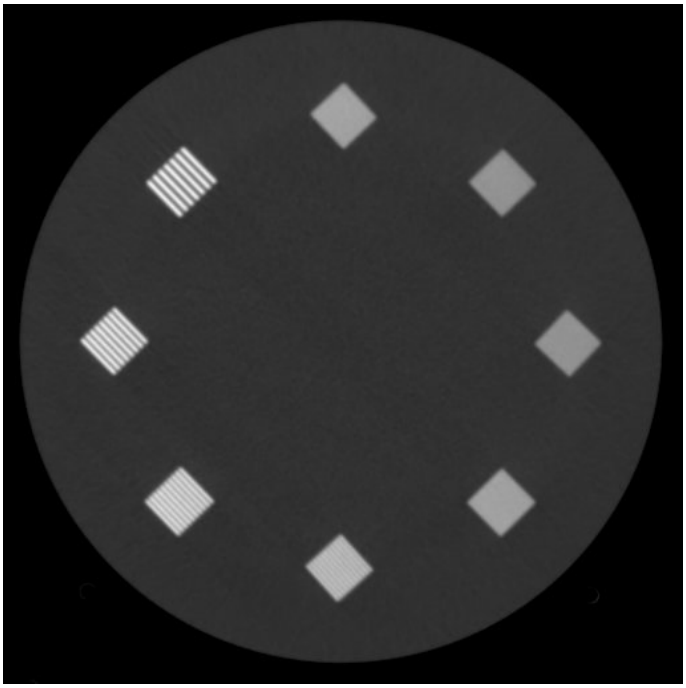
18. Image Metrics and Viewing
18.1. Introductory Statistics [3]
    18.1.1. Systematic and Random Error [3]
    18.1.2. Precision, Accuracy, and Reproducibility [3]
    18.1.3. Statistical Distributions: Poisson and Normal [2]
    18.1.4. Central Tendency: Mean, Median, and Mode [3]
    18.1.5. Dispersion: Standard Deviation, Variance, Range, and Percentiles [3]
    18.1.6. Correlation: Pearson vs Spearman [2]
    18.1.7. Confidence Intervals and Standard Error [3]
    18.1.8. Propagation of Error (Addition and Subtraction) [2]
18.2. Basic Hypothesis Testing and Regression [2]
    18.2.1. Chi-squared [2]
    18.2.2. T-tests and p-value [2]
    18.2.3. R^2 [2]
18.3. Imaging System Properties and Image Quality Metrics [3]
    18.3.1. Spatial and Frequency Domains [3]
    18.3.2. Contrast (Physical/Subject vs. Image vs. Display) [3]
    18.3.3. Spatial Resolution [3]
        18.3.3.1. Point/Line/Edge Spread Function [2]
        18.3.3.2. Full Width at Half Maximum (FWHM) [3]
        18.3.3.3. Modulation/Contrast Transfer Function (MTF/CTF) [1]
        18.3.3.4. Bar Phantom [3]
    18.3.4. Noise [3]

Module Specific References

1. ACR. (2017). *Computed Tomography Quality Control Manual*. American College of Radiology.
2. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
3. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.

Example Q&A:

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



(Image courtesy of William F. Sensakovic, PhD, Mayo Clinic Arizona)

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]ACR. (2017) *Computed Tomography Quality Control Manual;* [2]Bushberg. (2021) *The Essential Physics of Medical Imaging;* [3]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

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

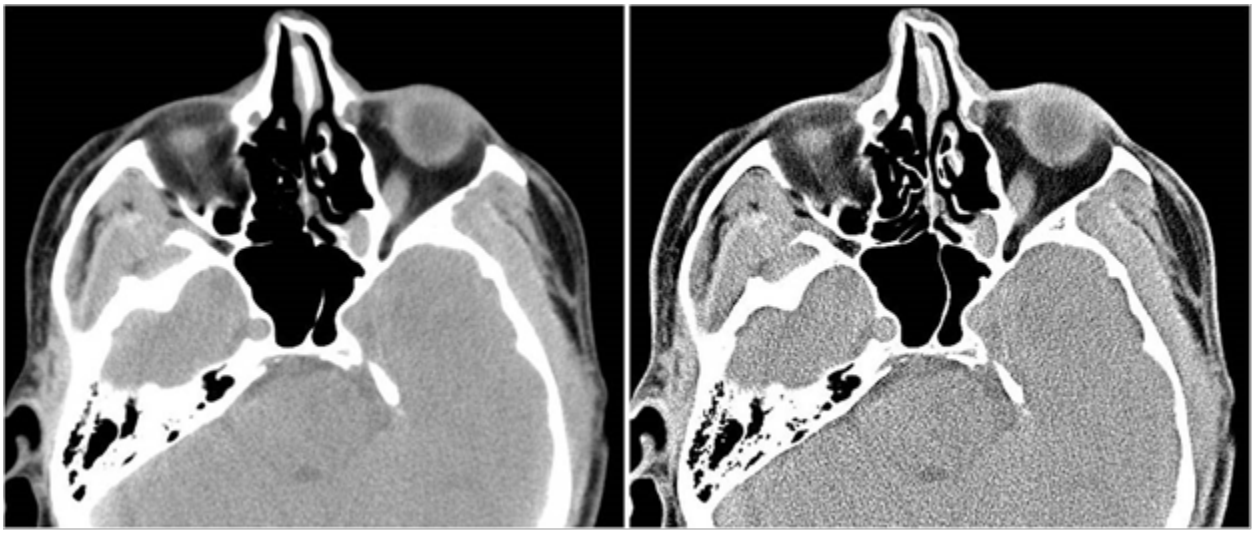
A. Modulation transfer function
B. Point spread function
C. Noise frequency
D. Signal-to-noise ratio

Answer: A – Modulation transfer function

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q3. Which of the following is increased in the image on the right?



(Image courtesy of William F. Sensakovic, PhD, Mayo Clinic Arizona)

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

Answer: A – Noise

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

References:[2]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

MODULE 19: IMAGE PROCESSING AND RECONSTRUCTION

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

Fundamental Knowledge:

1. Understand the basic concepts of window and leveling and the effects on image quality.
2. Recognize artifacts associated with flat-field gain calibrations.
3. Explain the method of Maximum Intensity Projection (MIP) image formation.

Clinical Applications and Problem Solving:

1. Compare and contrast the benefits of iterative reconstruction algorithms as compared to filtered back projection reconstructions.
2. Discuss the principles of dual energy techniques used in DEXA, Radiography, and CT imaging.
3. Recognize the effects of applying edge enhancement and smoothing processes on image quality.

Curriculum:

19. Image Processing
19.1. Pre-processing Corrections [2]
    19.1.1. Non-uniformity and Defect Correction [2]
        19.1.1.1. Flat-field Gain Calibrations [2]
        19.1.1.2. Normalization [1]
        19.1.1.3. Energy and Linearity Corrections [2]
19.2. Raw Image Processing [2]
    19.2.1. Segmentation and the Region-of-Interest [1]
        19.2.1.1. Automated vs. Semi-automated vs. Manual [1]
    19.2.2. Look-up Table (LUT) [1]
        19.2.2.1. Nonlinear Tables and Characteristic Curves [1]
        19.2.2.2. Histogram and Equalization [1]
    19.2.3. Frequency Processing [3]
        19.2.3.1. Edge Enhancement (e.g., Un-sharp Masking) [3]
        19.2.3.2. Smoothing (e.g., Pixel Averaging) [3]
19.3. Processed Image Manipulation [3]
    19.3.1. Window and Level [3]
    19.3.2. Edge Enhancement (CLAYHE) [3]
    19.3.3. Image Subtraction and Noise [2]
    19.3.4. Digital Magnification (Zoom) [2]
    19.3.5. Grayscale vs Color Viewing [1]
    19.3.6. Quantitative Analysis [2]
        19.3.6.1. Object Size Measurement [2]
        19.3.6.2. Shape and Texture [2]
        19.3.6.3. Motion and Flow [2]
19.4. Cross Sectional Image Reconstruction [3]

- 19.4.1. Methods [3]
  - 19.4.1.1. Simple Back-projection [1]
  - 19.4.1.2. Filtered Back-projection [3]
    - 19.4.1.2.1. Filter Selection [3]
    - 19.4.1.2.2. Cone-beam Reconstruction [1]
  - 19.4.1.3. Iterative Reconstruction Methods [3]
    - 19.4.1.3.1. Statistical [1]
    - 19.4.1.3.2. Model Based [1]
  - 19.4.1.4. Fourier Transformation [3]
- 19.4.2. Sinogram [2]
- 19.4.3. Attenuation Correction [2]

19.5. Dual-energy Processing [2]
- 19.5.1. Material Basis Pairs [2]
- 19.5.2. Material Subtraction [2]
- 19.5.3. Virtual Non-contrast Images [2]
- 19.5.4. Virtual Monoenergetic Images [2]

19.6. Post-reconstruction Image Display [3]
- 19.6.1. Multi and Curved Planar Reformats [3]
- 19.6.2. Maximum Intensity Projection (MIP) [3]
- 19.6.3. Shaded Surface Display [2]
- 19.6.4. Volume Rendering [2]

19.7. 3D Printing [1]

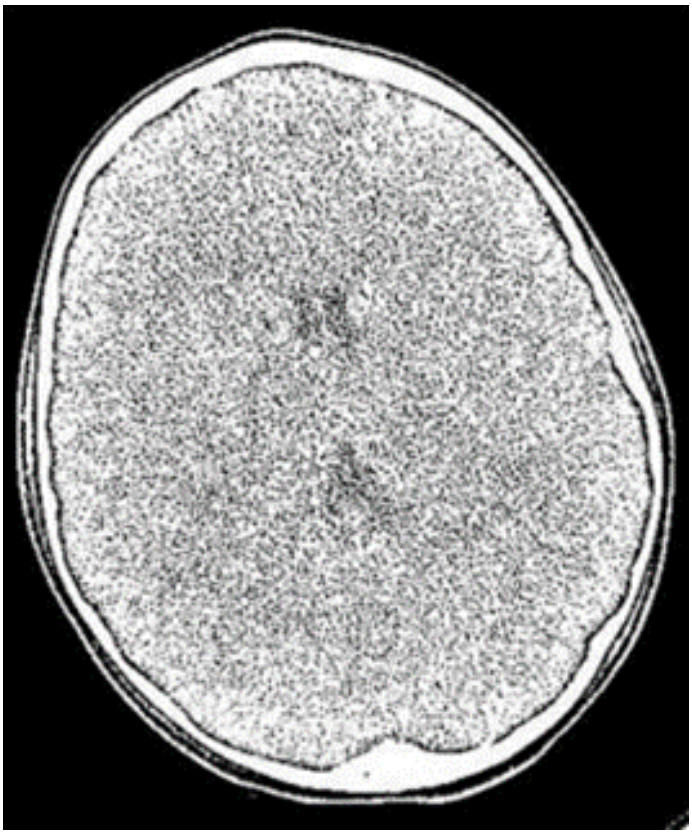
19.8. Radiomics [1]

Module Specific References

1. Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., & Boone, J. M. (2021). *The Essential Physics of Medical Imaging* (4th ed.). Wolters Kluwer.
2. Sensakovic, W. F., & Huda, W. (2023). *Review of Radiologic Physics* (5th ed.). Lippincott Williams & Wilkins.
3. Pisano, E. D., et al. (2000). Image processing algorithms for digital mammography: a pictorial essay. *Radiographics*, *20*(5), 1479-1491,
4. Bankman, I. (2009). *Handbook of Medical Image Processing and Analysis* (2nd ed.). Elsevier.
5. Bick, U., et al. (1995). Automated segmentation of digitized mammograms. *Academic radiology*, *2*(1), 1-9,

Example Q&A:

Q1. The CT image shown below is viewed at a window width of 2 HU and level of 2 HU. What single change below could be made to make the image more suitable for diagnostic viewing?



(Image courtesy of William F. Sensakovic, PhD, Mayo Clinic Arizona)

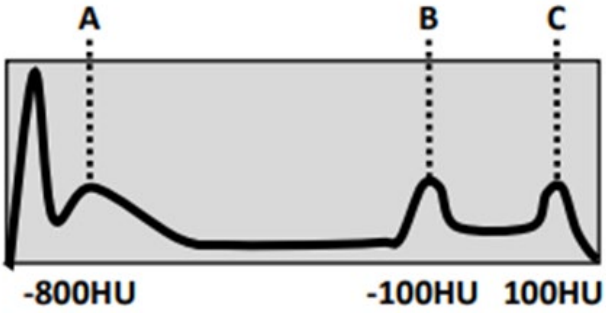
A. Increase window width
B. Decrease window width
C. Increase window level
D. Decrease window level

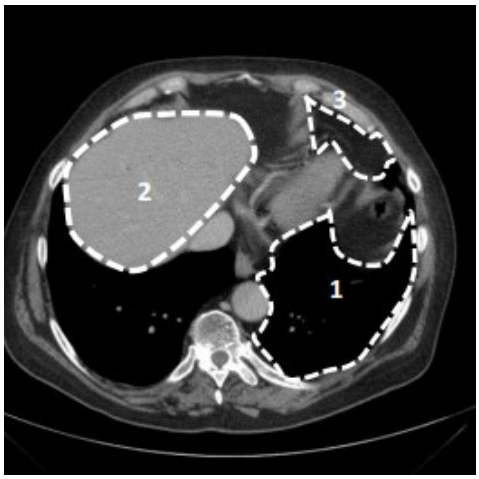
Answer: A – Increase window width

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q2. Match the outlined regions to their corresponding peaks on the histogram.





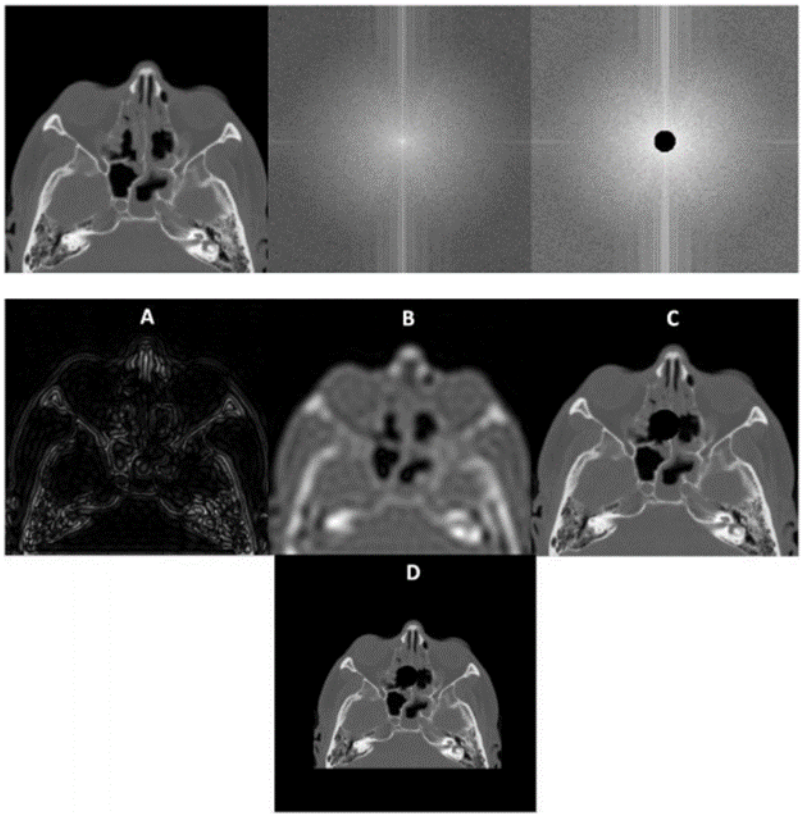
(Image courtesy of William F. Sensakovic, PhD, Mayo Clinic Arizona)

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

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [3]Pisano. (2000) *Image processing algorithms for digital mammography: a pictorial essay*

Q3. Given the original image (top left) and its Fourier Transform (top middle), which of the four images with letters below corresponds to altering the Fourier Transform as demonstrated in the top-right figure?



(Image courtesy of William F. Sensakovic, PhD, Mayo Clinic Arizona)

Answer: A

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

References:[1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [2]Sensakovic & Huda. (2023) *Review of Radiologic Physics*

Q4. The definition of segmentation in medical image processing is:

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

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

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*; [4]Bankman. (2009) *Handbook of Medical Image Processing and Analysis*; [5]Bick. (1995) *Automated segmentation of digitized mammograms*

Q5. Detection of a large, low-contrast object in a noisy image can be improved by:

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

Answer: B – Applying image smoothing

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

References: [1]Bushberg. (2021) *The Essential Physics of Medical Imaging*

MODULE 20: ARTIFICIAL INTELLIGENCE (AI)

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

Fundamental Knowledge:

1. Understand basic terminology related to Artificial Intelligence (AI).
2. Understand widely used-metrics for evaluation of AI systems.
3. Understand how Artificial Intelligence, Machine Learning, and Deep Learning relate to each other.
4. Understand different way humans work with AI systems.

Clinical Applications and Problem Solving:

1. Assess AI systems used in published literature.
2. Understand under what uses an AI system is off-label.

Curriculum:

20. Artificial Intelligence (AI)
20.1. Basic Terminology [3]
    20.1.1. Artificial Intelligence [3]
    20.1.2. Neutral Network, Neurons, and Nodes [3]
        20.1.2.1. Input, Output, Convolution, Hidden Layers [3]
        20.1.2.2. Cost Function, Gradient Descent, Backpropagation, Activation Function [1]
    20.1.3. Machine Learning [3]
    20.1.4. Deep Learning [2]
    20.1.5. Natural Language Processing [3]
    20.1.6. Training, Validation, & Testing Sets [3]
    20.1.7. Supervised vs. Unsupervised vs Reinforcement Learning [3]
    20.1.8. Hyperparameter [3]
    20.1.9. Feature [3]
20.2. Relationship between AI, Machine Learning, and Deep Learning [3]
20.3. Tasks [3]
    20.3.1. Segmentation [3]
    20.3.2. Localization [3]
    20.3.3. Classification [3]
    20.3.4. Regression/Prediction [3]
    20.3.5. Registration [1]
    20.3.6. Reconstruction/Synthesis [2]
    20.3.7. Natural Language Processing [3]
20.4. Assessment [3]
    20.4.1. Overfitting and Underfitting [3]
    20.4.2. Cross-validation and folds [3]
    20.4.3. Concept Drift vs Data Drift [3]
    20.4.4. Confusion Matrix [3]
        20.4.4.1. Precision, Recall, & F1 [3]
        20.4.4.2. True/False Positive & True/False Negative [3]

20.4.4.3. Sensitivity, Specificity, & Accuracy [3]
20.4.4.4. Matthew's Correlation Coefficient [2]
20.4.4.5. Receiver Operator Characteristics & Area Under the Curve [2]
20.4.5. Saliency and activation maps [1]
20.4.6. Distance metrics (e.g., Dice/Jaccard Index, Root-Mean-Square Error, Structure Similarity Index, etc.) [3]
20.5. Human-AI interaction types [3]
20.5.1. Co-read [3]
20.5.2. Pre-read and Triage [3]
20.5.3. Post-read [3]
20.5.4. Methods of making observer aware (e.g., marker size and shape) [1]
20.6. FDA clearance indications, and off-label use [2]

Module Specific References

1. Goodfellow, I., Bengio, Y., & Courville, A. (2016). *Deep Learning* (1st ed.). MIT press.
2. Sidey-Gibbons, J. A., & Sidey-Gibbons, C. J. (2019). Machine learning in medicine: a practical introduction. *BMC medical research methodology*, *19*, 1-18,

Example Q&A:

Q1. Which of the following is an example of a Machine Learning (ML) application?

A. A calculator performing basic arithmetic
B. An algorithm that predicts survival with parameters learned from historical data
C. A computer program that follows a fixed set of rules
D. A website to facilitate literature search

Answer: B – An algorithm predicting surviving based on historical data

Explanation: ML applications often involve analyzing large amounts of data to identify patterns and make predictions or decisions, such as forecasting stock market trends.

References:[1]Goodfellow. (2016) *Deep Learning*

Q2. Deep Learning (DL) is primarily characterized by:

A. Simple linear models
B. Neural networks with multiple hidden layers
C. Basic arithmetic calculations
D. Rule-based programming

Answer: B – Neural networks with multiple hidden layers

Explanation: Deep Learning is a subset of ML characterized by deep neural networks with multiple hidden layers (hence "deep") that can learn from a large amount of data. These layers enable the model to learn complex patterns.

References:[1]Goodfellow. (2016) *Deep Learning*

Q3. In the context of ML and AI, 'training' a model refers to:

A. Educating users on how to use the software
B. Feeding the model example data and adjusting its weights to improve performance
C. Physical exercises to improve the model's endurance
D. Testing the model on new, unseen data

Answer: B – Feeding the model example data and adjusting its weights to improve performance

Explanation: Training a model involves providing it with data and allowing it to adjust its weights in neural networks to improve its ability to make predictions or decisions.

References:[1]Goodfellow. (2016) *Deep Learning*; [2]Sidey-Gibbons & Sidey-Gibbons. (2019) *Machine learning in medicine: a practical introduction*

Q4. What is a 'test dataset' in ML?

A. A set of data used to train the model
B. Independent data used to evaluate the performance of a model after training is complete
C. The initial set of data for setting up the model
D. The dataset used for user acceptance testing

Answer: B – Independent data used to evaluate the performance of a model after training is complete

Explanation: A test dataset is a set of data separate from the training data. It is used to evaluate the performance and generalization ability of the model on new, unseen data.

References:[1]Goodfellow. (2016) *Deep Learning*; [2]Sidey-Gibbons & Sidey-Gibbons. (2019) *Machine learning in medicine: a practical introduction*

Q5. Which of the following is a commonly used metric for evaluating classification model performance?

A. Runtime
B. Precision and recall
C. File size
D. Number of layers

Answer: B – Precision and recall

Explanation: Precision and recall are important metrics for evaluating the performance of classification models. Precision measures the accuracy of positive predictions, while recall measures the model's ability to find all the relevant cases within a dataset.

References:[1]Goodfellow. (2016) *Deep Learning*

Q6. What does 'overfitting' mean in the context of ML models?

A. The model performs well on the training data but poorly on unseen data
B. The model is too simple to capture the patterns in the data
C. The model runs too quickly
D. The model is physically too large for the computer

Answer: A – The model performs well on the training data but poorly on unseen data

Explanation: Overfitting occurs when a model learns the training data too well, including its noise and outliers, resulting in poor performance on new, unseen data due to a lack of generalization.

References:[1]Goodfellow. (2016) *Deep Learning*; [2]Sidey-Gibbons & Sidey-Gibbons. (2019) *Machine learning in medicine: a practical introduction*

Q7. What is a key difference between supervised and unsupervised learning in deep learning?

A. Supervised learning requires labeled data, while unsupervised learning does not
B. Unsupervised learning is faster than supervised learning
C. Supervised learning can only be used for classification tasks
D. Unsupervised learning uses reinforcement learning techniques

Answer: A – Supervised learning requires labeled data, while unsupervised learning does not

Explanation: Supervised learning algorithms learn from labeled data, meaning each data point in the training set is paired with the correct output. In contrast, unsupervised learning algorithms work with unlabeled data, trying to find hidden patterns or structures without guidance from labels.

References:[1]Goodfellow. (2016) *Deep Learning*; [2]Sidey-Gibbons & Sidey-Gibbons. (2019) *Machine learning in medicine: a practical introduction*