

**Diagnostic Radiology Residents Physics Curriculum**  
**AAPM Subcommittee of the Medical Physics Education of Physicians Committee**  
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Authors: (see complete list in Appendix A)

History and comments: (see complete details in Appendix B)

**Preface**

This curriculum describes the core physics knowledge related to medical imaging that a radiologist should know when graduating from an accredited radiology residency program. The depth and order of presentation is left to the institution. The weighting of the subject material is a relative indicator of the importance of each area of study. It does not reflect the ABR weighting of topics on the physics certification examination for radiologists. The subject material described in this curriculum should be taught in a clinically relevant manner.

<b>Basic Science</b>	<b>Weighting</b>
1. Structure of the Atom	2
2. Electromagnetic (EM) Radiation	2
3. Particulate Radiation	1
4. Interaction of Radiation with Matter	4
5. Radiation Units	2
6. X-ray Production	5
7. Basic Imaging Science and Technology	6
8. Radiation Biology	8
9. Radiation Protection	9
<b>Imaging Modalities</b>	
10. X-ray Projection Imaging Concepts and Detectors	6
11. General Radiography	6
12. Mammography	3
13. Fluoroscopy	3
14. CT	8
15. Ultrasound	9
16. Magnetic Resonance	12
17. Nuclear Medicine	14
<b>Total</b>	<b>100</b>

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# **Basic Science**

## **1. Structure of the Atom**

- 1.1. Composition
  - 1.1.1. Electrons
  - 1.1.2. Nucleus
- 1.2. Electronic Structure
  - 1.2.1. Electron Orbits
  - 1.2.2. Orbital Nomenclature
  - 1.2.3. Binding Energy
  - 1.2.4. Electron Transitions
  - 1.2.5. Characteristic Radiation
  - 1.2.6. Auger Electrons
- 1.3. Nuclear Structure
  - 1.3.1. Composition
  - 1.3.2. Nuclear Force
  - 1.3.3. Mass Defect
  - 1.3.4. Binding Energy
  - 1.3.5. Fission
  - 1.3.6. Fusion
  - 1.3.7. Nuclear Instability - Overview
    - 1.3.7.1. Beta (negative electron) Decay
    - 1.3.7.2. Positron (positive electron) Decay
    - 1.3.7.3. Electron Capture
    - 1.3.7.4. Isomeric Transition
  - 1.3.8. Classification of Nuclides

## **2. Electromagnetic (EM) Radiation**

- 2.1. Wave-Particle Duality
  - 2.1.1. Wave Characteristics
  - 2.1.2. Particle Characteristics
- 2.2. Electromagnetic Spectrum
  - 2.2.1. Ionizing
  - 2.2.2. Non-ionizing

## **3. Particulate Radiation**

- 3.1. Light Particles
- 3.2. Heavy-Charged Particles
- 3.3. Uncharged Particles

## **4. Interaction of Radiation with Matter**

- 4.1. Charged Particle Interactions
  - 4.1.1. Ionization/Excitation
  - 4.1.2. Bremsstrahlung
  - 4.1.3. Secondary Ionization
    - 4.1.3.1. Specific Ionization
    - 4.1.3.2. Linear Energy Transfer (LET)
  - 4.1.4. Positron Annihilation
- 4.2. Neutron Interactions

- 4.3. Photon Interactions
  - 4.3.1. Coherent Scattering
  - 4.3.2. Compton Scattering
  - 4.3.3. The Photoelectric Effect
  - 4.3.4. Pair Production
  - 4.3.5. Interactions in Tissues
  - 4.3.6. Contrast Media
- 4.4. Photon Attenuation
  - 4.4.1. Linear Attenuation Coefficient
  - 4.4.2. Mass Attenuation Coefficient
  - 4.4.3. Attenuation Equation
  - 4.4.4. Poly-energetic X-Ray Beams
  - 4.4.5. Half -value Layer (HVL)
    - 4.4.5.1. Effective Energy
    - 4.4.5.2. Beam Hardening
    - 4.4.5.3. Geometry
  - 4.4.6. Mass Energy Absorption Coefficient
- 5. **Radiation Units**
  - 5.1. System of Units
    - 5.1.1. SI
    - 5.1.2. Classical
  - 5.2. Exposure
    - 5.2.1. coulomb/kilogram
    - 5.2.2. Roentgen
  - 5.3. KERMA
  - 5.4. Absorbed Dose
    - 5.4.1. Gray
    - 5.4.2. Rad
  - 5.5. Imparted Energy
  - 5.6. Equivalent Dose
    - 5.6.1. Radiation Weighting Factors
    - 5.6.2. Sievert
    - 5.6.3. rem
  - 5.7. Effective Dose
    - 5.7.1. Tissue Weighting Factors
    - 5.7.2. Sievert
    - 5.7.3. rem
    - 5.7.4. Importance in Radiation Protection
- 6. **X-ray Production**
  - 6.1. Properties of X Rays
    - 6.1.1. Bremsstrahlung
      - 6.1.1.1. Importance in Imaging
      - 6.1.1.2. Influence of Electron Energy
      - 6.1.1.3. Influence of Target Material
      - 6.1.1.4. Influence of Filtration
    - 6.1.2. Characteristic Radiation

- 6.1.2.1. Importance in Imaging
- 6.1.2.2. Influence of Target Material
- 6.1.2.3. Influence of Filtration
- 6.2. X Ray Tube
  - 6.2.1. Cathode
    - 6.2.1.1. Filament
    - 6.2.1.2. Focusing Cup
    - 6.2.1.3. Biasing
    - 6.2.1.4. Filament and Tube Current
    - 6.2.1.5. Focal Spot Blooming
    - 6.2.1.6. Space Charge
  - 6.2.2. Anode
    - 6.2.2.1. Composition
    - 6.2.2.2. Configuration
    - 6.2.2.3. High-Speed Rotating Anode
    - 6.2.2.4. Line-Focus Principle
    - 6.2.2.5. Focal Spot
    - 6.2.2.6. Heel Effect
    - 6.2.2.7. Off-Focus Radiation
    - 6.2.2.8. Overheating
  - 6.2.3. Application-Specific Tubes
    - 6.2.3.1. Mammography
    - 6.2.3.2. Straton
- 6.3. Generators
  - 6.3.1. Single-Phase
  - 6.3.2. Three-Phase
  - 6.3.3. High-Frequency
  - 6.3.4. Technique Factors
    - 6.3.4.1. kVp
    - 6.3.4.2. mA
    - 6.3.4.3. Time
    - 6.3.4.4. Automatic Exposure Control (AEC)
    - 6.3.4.5. Technique Charts
- 6.4. X-ray Beam
  - 6.4.1. Beam Filtration
    - 6.4.1.1. Inherent
    - 6.4.1.2. Added (Al, Cu, Mo, Rh, other)
    - 6.4.1.3. Minimum HVL
    - 6.4.1.4. Shaped Filters
  - 6.4.2. Spectrum
  - 6.4.3. Collimators
    - 6.4.3.1. Field Size Limitation
    - 6.4.3.2. Light/X-Ray Alignment
    - 6.4.3.3. Effect on Image Quality
    - 6.4.3.4. Importance to Safety
  - 6.4.4. Geometry

- 6.4.4.1. Source-to-Image Receptor Distance (SID)
- 6.4.4.2. Magnification
- 7. **Basic Imaging Science and Technology**
  - 7.1. Basic Statistics
    - 7.1.1. Systematic and Random Error
    - 7.1.2. Precision and Accuracy
    - 7.1.3. Statistical Distributions
    - 7.1.4. Mean, Median and Mode
    - 7.1.5. Variance
    - 7.1.6. Confidence Intervals
    - 7.1.7. Propagation of Error
    - 7.1.8. Statistical Process Control
  - 7.2. Image Properties
    - 7.2.1. Image Representations
      - 7.2.1.1. Spatial
      - 7.2.1.2. Frequency
      - 7.2.1.3. Temporal
      - 7.2.1.4. Fourier and Other Transforms
    - 7.2.2. Contrast Degradation Processes
    - 7.2.3. Spatial Resolution
      - 7.2.3.1. Point Spread Function (PSF)
      - 7.2.3.2. Line Spread Function (LSF)
      - 7.2.3.3. Full-Width-at-Half-Maximum (FWHM)
      - 7.2.3.4. Modulation Transfer Function (MTF)
    - 7.2.4. Noise
      - 7.2.4.1. Quantum Mottle
      - 7.2.4.2. Electronic
      - 7.2.4.3. Structured
      - 7.2.4.4. Other Sources of Noise
    - 7.2.5. Dynamic Range
    - 7.2.6. Contrast Noise Ratio (CNR), Signal to Noise Ratio (SNR), Detective Quantum Efficiency (DQE), Quantum Detection Efficiency (QDE)
    - 7.2.7. Temporal Resolution
    - 7.2.8. Sampling and Quantization
      - 7.2.8.1. Analog to Digital Conversion (ADC) and Digital to Analog Conversion (DAC)
      - 7.2.8.2. Aliasing
      - 7.2.8.3. Nyquist Limit
      - 7.2.8.4. Bit Depth
  - 7.3. Generic Image Processing
    - 7.3.1. Pre-processing
      - 7.3.1.1. Non-Uniformity Correction
      - 7.3.1.2. Defect Corrections
    - 7.3.2. Segmentation
      - 7.3.2.1. Collimation
      - 7.3.2.2. Value of Interest

- 7.3.3. Grayscale Processing
  - 7.3.3.1. Window/Level
  - 7.3.3.2. Characteristic Curves
  - 7.3.3.3. Look-Up Tables
- 7.3.4. Frequency Processing
  - 7.3.4.1. Edge Enhancement
  - 7.3.4.2. Noise Reduction
  - 7.3.4.3. Equalization
- 7.3.5. Reconstruction
  - 7.3.5.1. Simple Back-Projection
  - 7.3.5.2. Filtered Back-Projection
  - 7.3.5.3. Iterative Reconstruction Methods
  - 7.3.5.4. Sinogram
- 7.3.6. Three-dimensional
  - 7.3.6.1. Multi-Planar Reconstruction
  - 7.3.6.2. Maximum-Intensity Projection
  - 7.3.6.3. Volume Rendering/Surface Shading
  - 7.3.6.4. Quantitative Assessments
- 7.3.7. Image Fusion/Registration
- 7.3.8. Computer-Aided Detection (CAD) and Diagnosis
- 7.4. Display
  - 7.4.1. Display Technologies
    - 7.4.1.1. Hard-Copy Printers
    - 7.4.1.2. Film
    - 7.4.1.3. Cathode Ray Tube (CRT)
    - 7.4.1.4. Liquid Crystal Display (LCD)
    - 7.4.1.5. Other Displays (e.g., plasma, projection, etc.)
  - 7.4.2. Display Settings
    - 7.4.2.1. Film Quality Control
    - 7.4.2.2. Luminance
    - 7.4.2.3. Matrix Size
    - 7.4.2.4. Grayscale Display Function Calibration
    - 7.4.2.5. Display Quality Control
  - 7.4.3. Viewing Conditions
    - 7.4.3.1. Viewing Distance, Image and Pixel Size
    - 7.4.3.2. Workstation Adjustments
    - 7.4.3.3. Adaptation/Masking
    - 7.4.3.4. Ambient Lighting/ Illuminance
- 7.5. Perception
  - 7.5.1. Human Vision
    - 7.5.1.1. Visual Acuity
    - 7.5.1.2. Contrast Sensitivity
    - 7.5.1.3. Astigmatism
    - 7.5.1.4. Conspicuity
  - 7.5.2. Metrics of Observer Performance
    - 7.5.2.1. Predictive Values

- 7.5.2.2. Sensitivity, Specificity and Accuracy
- 7.5.2.3. Contrast-Detail
- 7.5.2.4. Receiver Operating Characteristic (ROC) Curve
- 7.5.3. Perceptual Influence of Technology (e.g., CAD)
- 7.6. Informatics
  - 7.6.1. Basic Computer Terminology
  - 7.6.2. Integrating Healthcare Enterprise (IHE)
    - 7.6.2.1. PACS
    - 7.6.2.2. Radiology Information System (RIS), Hospital Information System (HIS)
    - 7.6.2.3. Electronic Medical Record (EMR)
    - 7.6.2.4. Health Level 7 (HL7)
    - 7.6.2.5. DICOM
  - 7.6.3. Networks
    - 7.6.3.1. Hardware
    - 7.6.3.2. Bandwidth
    - 7.6.3.3. Communication Protocols
  - 7.6.4. Film Digitizers
  - 7.6.5. Storage
    - 7.6.5.1. Hardware
    - 7.6.5.2. Storage Requirements
    - 7.6.5.3. Disaster Recovery
  - 7.6.6. DICOM
    - 7.6.6.1. Modality Worklist
    - 7.6.6.2. Image and Non-Image Objects
    - 7.6.6.3. Components and Terminology
    - 7.6.6.4. DICOM Conformance
  - 7.6.7. Data Compression
    - 7.6.7.1. Clinical Impact
    - 7.6.7.2. Lossy
    - 7.6.7.3. Lossless
    - 7.6.7.4. Image/Video Formats
  - 7.6.8. Security and Privacy
    - 7.6.8.1. Encryption
    - 7.6.8.2. Firewalls
    - 7.6.8.3. Biometrics
    - 7.6.8.4. Health Insurance Portability and Accountability Act (HIPAA)
- 8. **Radiation Biology**
  - 8.1. Principles
    - 8.1.1. Linear Energy Transfer
    - 8.1.2. Relative Biological Effectiveness
    - 8.1.3. Weighting Factors
  - 8.2. Molecular Effects of Radiation
    - 8.2.1. Direct Effects
    - 8.2.2. Indirect Effects
    - 8.2.3. Effects of Radiation on DNA

- 8.3. Cellular Effects of Radiation
  - 8.3.1. Law of Bergonié and Tribondeau
  - 8.3.2. Radiosensitivity of Different Cell Types
  - 8.3.3. Cell Cycle Radiosensitivity
  - 8.3.4. Cell Damage
    - 8.3.4.1. Division Delay
    - 8.3.4.2. Mitotic Death
    - 8.3.4.3. Apoptosis
  - 8.3.5. Cell Survival Curves
  - 8.3.6. Repair
- 8.4. System Effects of Radiation
  - 8.4.1. Tissues
  - 8.4.2. Organs
  - 8.4.3. Whole Body
  - 8.4.4. Population
- 8.5. Deterministic (Non-Stochastic) Effects
  - 8.5.1. Radiation Syndromes
    - 8.5.1.1. Hematopoetic
    - 8.5.1.2. Gastrointestinal
    - 8.5.1.3. Cerebrovascular
    - 8.5.1.4. Sequence of Events
    - 8.5.1.5. LD 50/60
    - 8.5.1.6. Monitoring and Treatment
  - 8.5.2. Other Effects
    - 8.5.2.1. Erythema
    - 8.5.2.2. Epilation
    - 8.5.2.3. Cataracts
    - 8.5.2.4. Sterility
- 8.6. Probabilistic (Stochastic) Radiation Effects
  - 8.6.1. Radiation Epidemiology–Case Studies
    - 8.6.1.1. Atomic Bomb Survivors
    - 8.6.1.2. Ankylosing Spondylitis
    - 8.6.1.3. Epilation for Tinea Capita
    - 8.6.1.4. Thorotrast
    - 8.6.1.5. TB Sanitoria
    - 8.6.1.6. Postpartum Mastitis
    - 8.6.1.7. Uranium Miners
    - 8.6.1.8. Marshall Island Residents
    - 8.6.1.9. Radium Dial Painters
    - 8.6.1.10. Early Radiologists
  - 8.6.2. Carcinogenesis
    - 8.6.2.1. Radiation-Induced Cancers
      - 8.6.2.1.1. Leukemia
      - 8.6.2.1.2. Solid Tumors
    - 8.6.2.2. Spontaneous Rate
    - 8.6.2.3. Latency

- 8.6.3. Mutagenesis
  - 8.6.3.1. Baseline Mutation Rate
  - 8.6.3.2. Doubling Dose
- 8.6.4. Teratogenesis
  - 8.6.4.1. Developmental Effects
  - 8.6.4.2. Childhood Leukemia
  - 8.6.4.3. Gestational Sensitivity
- 8.7. Radiation Risk
  - 8.7.1. Risk-Benefit in Radiology
  - 8.7.2. Risk Models
    - 8.7.2.1. Relative
    - 8.7.2.2. Absolute
  - 8.7.3. Information Sources
    - 8.7.3.1. Biological Effects of Ionizing Radiation Reports (e.g., BEIR VII Phase II)
    - 8.7.3.2. International Council on Radiation Protection (ICRP)
    - 8.7.3.3. National Council on Radiation Protection (NCRP) (i.e, Report 116)
    - 8.7.3.4. United Nations Scientific Committee on the Effects of Atomic Radiation Reports (UNSCEAR)
  - 8.7.4. Perception of Risk
- 8.8. Dose Response Models
  - 8.8.1. Linear, No-Threshold (LNT)
  - 8.8.2. Linear-Quadratic
  - 8.8.3. Hormesis
- 9. Radiation Protection**
  - 9.1. Background Radiation
    - 9.1.1. Cosmic
    - 9.1.2. Terrestrial
    - 9.1.3. Internal
    - 9.1.4. Radon
  - 9.2. Non-Medical Sources
    - 9.2.1. Nuclear Power Emissions
    - 9.2.2. Tobacco
    - 9.2.3. Technologically-Enhanced Naturally Occurring Radioactive Material (TENORM) (Pipe Scale)
    - 9.2.4. Fallout
  - 9.3. Medical Sources – Occupational and Patient Doses
    - 9.3.1. Projection Radiography
    - 9.3.2. Fluoroscopy
    - 9.3.3. Interventional/Angiography
    - 9.3.4. CT
    - 9.3.5. Sealed Source Radioactive Material
    - 9.3.6. Unsealed Radioactive Material
    - 9.3.7. Therapeutic External Radiation
    - 9.3.8. Non-Ionizing
  - 9.4. Persons at Risk

- 9.4.1. Occupational
- 9.4.2. Non-Occupational Staff
- 9.4.3. Members of the Public
- 9.4.4. Fetus
- 9.4.5. Patient
  - 9.4.5.1. Adult
  - 9.4.5.2. Child
  - 9.4.5.3. Pregnancy known
  - 9.4.5.4. Pregnancy status unknown
- 9.5. Dose limits
  - 9.5.1. Occupational Dose Limits
    - 9.5.1.1. Effective Dose Equivalent
    - 9.5.1.2. Specific Organ
    - 9.5.1.3. Pregnant Workers
  - 9.5.2. Members of the Public
    - 9.5.2.1. General
    - 9.5.2.2. Caregivers
    - 9.5.2.3. Limit to Minors
- 9.6. Radiation Detectors
  - 9.6.1. Personnel Dosimeters
    - 9.6.1.1. Whole Body
    - 9.6.1.2. Extremity
    - 9.6.1.3. Emergency/Self-Reading
    - 9.6.1.4. Dosimeter Placement
    - 9.6.1.5. Common Problems
  - 9.6.2. Area Monitors
    - 9.6.2.1. Ion Chambers
    - 9.6.2.2. Geiger-Mueller (GM)
    - 9.6.2.3. Scintillators
    - 9.6.2.4. Thermoluminescent Dosimeters (TLDs)
    - 9.6.2.5. Film
- 9.7. Principles of Radiation Protection
  - 9.7.1. Time
  - 9.7.2. Distance
  - 9.7.3. Shielding
    - 9.7.3.1. Facility
    - 9.7.3.2. Workers
    - 9.7.3.3. Caregivers
    - 9.7.3.4. Patients
    - 9.7.3.5. Members of the Public
    - 9.7.3.6. Types of Materials
  - 9.7.4. Contamination Control
  - 9.7.5. As Low As Reasonably Achievable (ALARA)
  - 9.7.6. Procedure Appropriateness
- 9.8. Factors Affecting Patient Dose
  - 9.8.1. Radiography

- 9.8.1.1. Technique (e.g., kVp, mA [mAs])
- 9.8.1.2. Source-to-Detector Distance
- 9.8.1.3. Beam Filtration and Grid
- 9.8.1.4. Field Size
- 9.8.1.5. Receptor Speed
- 9.8.2. Fluoroscopy/Interventional Radiology
  - 9.8.2.1. Technique
  - 9.8.2.2. Acquisition Mode
  - 9.8.2.3. Exposure Time
  - 9.8.2.4. Last-Image Hold
  - 9.8.2.5. Pulsed Exposure
  - 9.8.2.6. Magnification
  - 9.8.2.7. Collimation
  - 9.8.2.8. Tube-to-Patient Distance
  - 9.8.2.9. Operator Training
- 9.8.3. Computed Tomography (CT)
  - 9.8.3.1. Beam Width and Pitch
  - 9.8.3.2. Variable mA
  - 9.8.3.3. Scan Length
  - 9.8.3.4. Number of Passes
  - 9.8.3.5. Technique Selection
  - 9.8.3.6. Pediatric Patients
- 9.8.4. Mammography
  - 9.8.4.1. Exposure Limits (e.g., mandatory accreditation standards)
  - 9.8.4.2. Techniques
  - 9.8.4.3. Compression
  - 9.8.4.4. Screening Exams
  - 9.8.4.5. Diagnostic Examinations including Magnification
- 9.8.5. Nuclear Medicine
  - 9.8.5.1. Source Control (e.g., patient location)
  - 9.8.5.2. Administered Pharmaceutical, Isotope and Activity
  - 9.8.5.3. Contamination Control
  - 9.8.5.4. Patient Flow
- 9.9. Advisory Bodies
  - 9.9.1. Radiation-Related
    - 9.9.1.1. International Commission on Radiological Protection
    - 9.9.1.2. National Council on Radiation Protection and Measurements
    - 9.9.1.3. Conference of Radiation Control Program Directors
    - 9.9.1.4. International Atomic Energy Agency
  - 9.9.2. Accreditation Organizations (X-Ray and Nuclear Medicine)
    - 9.9.2.1. Joint Commission on Accreditation of Healthcare Organizations
    - 9.9.2.2. American College of Radiology
    - 9.9.2.3. InterSocietal Accreditation Commission
  - 9.9.3. Other
    - 9.9.3.1. National Academy of Sciences

- 9.9.3.2. Institute of Medicine
- 9.9.3.3. International ElectroTechnical Commission
- 9.9.3.4. Joint Commission on Accreditation of Healthcare Organizations
- 9.10. Regulatory Agencies
  - 9.10.1. U.S. Nuclear Regulatory Commission/Agreement States
    - 9.10.1.1. 10 CFR Parts 19, 20, 30, 32, 35, 110
    - 9.10.1.2. Guidance Documents (e.g., NUREG 1556, Vols. 9 & 11)
    - 9.10.1.3. Regulatory Guides
  - 9.10.2. States – for Machine-Producing Sources (e.g., Suggested State Regulations)
  - 9.10.3. U.S. Food and Drug Administration
    - 9.10.3.1. Center for Devices and Radiological Health
    - 9.10.3.2. Center for Drug Evaluation and Research
  - 9.10.4. U.S. Office of Human Research Protections
  - 9.10.5. U.S. Department of Transportation
  - 9.10.6. U.S. Department of Labor (OSHA)
- 9.11. Radiation Safety in Nuclear Medicine
  - 9.11.1. Surveys
    - 9.11.1.1. Area
    - 9.11.1.2. Wipe Test
    - 9.11.1.3. Spills
  - 9.11.2. Ordering, Receiving, and Unpacking Radioactive Materials
  - 9.11.3. Contamination Control
  - 9.11.4. Radioactive Waste Management
  - 9.11.5. Procedures
    - 9.11.5.1. Diagnostic (e.g., 10 CFR 35.200 or equivalent Agreement State)
    - 9.11.5.2. Therapeutic (e.g., 10 CFR 35.300 or equivalent Agreement State)
  - 9.11.6. Special Considerations
    - 9.11.6.1. Pregnant Patients
    - 9.11.6.2. Breast-Feeding Patients
    - 9.11.6.3. Caregivers
    - 9.11.6.4. Patient Release
- 9.12. Estimating Patient and Fetal Dose (Procedure-Specific Doses)
  - 9.12.1. Radiography
  - 9.12.2. Mammography
  - 9.12.3. Fluoroscopy
  - 9.12.4. Computed Tomography (CT)
  - 9.12.5. Nuclear Medicine
- 9.13. Shielding
  - 9.13.1. Design Philosophy
  - 9.13.2. Primary
  - 9.13.3. Secondary
  - 9.13.4. Leakage
  - 9.13.5. Controlled/Uncontrolled areas
  - 9.13.6. Definitions
    - 9.13.6.1. Use Factor

- 9.13.6.2. Occupancy
- 9.13.6.3. Workload
- 9.13.7. Examples of Shielding Design
  - 9.13.7.1. Diagnostic
  - 9.13.7.2. PET
  - 9.13.7.3. Hot Lab/Nuclear Medicine
- 9.14. Radiological Emergencies
  - 9.14.1. Incidents
    - 9.14.1.1. Nuclear Power
    - 9.14.1.2. Military Equipment
    - 9.14.1.3. Transportation Accidents
    - 9.14.1.4. Research Lab / Radiopharmacy Accidents
  - 9.14.2. Purposeful Exposures
    - 9.14.2.1. Nuclear Detonation
    - 9.14.2.2. Radiological Dispersion Device (RDD)
    - 9.14.2.3. Environmental Contamination
  - 9.14.3. Treatment of Radiological Casualties
    - 9.14.3.1. Notification/Patient Arrival
    - 9.14.3.2. Triage/Evaluation/Initial Treatment
    - 9.14.3.3. Exposure/External and Internal Contamination
    - 9.14.3.4. Radiological Assessment
    - 9.14.3.5. Medical Management
    - 9.14.3.6. Oak Ridge Radiation Emergency Assistance Center

## **Imaging Modalities**

### **10. X-ray Projection Imaging Concepts and Detectors**

- 10.1.1. Radiography Concepts
- 10.1.2. Geometry
  - 10.1.2.1. Source-to-Image Receptor Distance/Source-to-Object Distance (SID/SOD)
  - 10.1.2.2. Magnification
  - 10.1.2.3. Inverse Square Law
- 10.1.3. Radiographic Contrast
  - 10.1.3.1. Subject
  - 10.1.3.2. Object
  - 10.1.3.3. Detector
- 10.1.4. Scatter and Scatter Reduction
  - 10.1.4.1. Scatter-to-Primary Ratio
  - 10.1.4.2. Scatter Fraction
  - 10.1.4.3. Collimation
  - 10.1.4.4. Anti-Scatter Grids
  - 10.1.4.5. Air Gap
- 10.1.5. Artifacts and Image Degradation
  - 10.1.5.1. Geometrical Distortion
  - 10.1.5.2. Focal Spot Blur/Penumbra
  - 10.1.5.3. Grid Artifacts/Cutoff

- 10.1.5.4. Motion
- 10.1.5.5. Superimposition
- 10.2. Radiographic Detectors
  - 10.2.1. Screen/Film
    - 10.2.1.1. Phosphors
    - 10.2.1.2. Film
    - 10.2.1.3. Screen/Film Systems
    - 10.2.1.4. Latent Image Formation
    - 10.2.1.5. Chemical Processing
    - 10.2.1.6. Characteristic Curve
    - 10.2.1.7. Spatial and Contrast Resolution
    - 10.2.1.8. Artifacts
  - 10.2.2. Computed Radiography (CR)
    - 10.2.2.1. Storage Phosphors
    - 10.2.2.2. Latent Image Formation
    - 10.2.2.3. Image Digitization
    - 10.2.2.4. Pre-Processing (e.g., gain and bad-pixel correction)
    - 10.2.2.5. Imaging Characteristics
    - 10.2.2.6. Artifacts
  - 10.2.3. Direct Digital Radiography (DR)
    - 10.2.3.1. Semiconductor and Thin-Film Transistor
    - 10.2.3.2. Image Formation and Readout
    - 10.2.3.3. Pre-processing (e.g., gain and bad-pixel correction)
    - 10.2.3.4. Imaging Characteristics
    - 10.2.3.5. Artifacts
  - 10.2.4. Indirect DR
    - 10.2.4.1. Phosphor, Photo Diodes and Thin Film Transistor
    - 10.2.4.2. Image Formation and Readout
    - 10.2.4.3. Preprocessing (e.g., gain and bad-pixel correction)
    - 10.2.4.4. Imaging Characteristics
    - 10.2.4.5. Artifacts
- 11. **General Radiography**
  - 11.1. System Components
    - 11.1.1. Tube
    - 11.1.2. Filtration
    - 11.1.3. Collimation
    - 11.1.4. Automatic Exposure Control (AEC)
    - 11.1.5. Grids and Bucky Factors
    - 11.1.6. Compensation Filters
  - 11.2. Geometrical Requirements
    - 11.2.1. Focal Spot Size
    - 11.2.2. Collimation
    - 11.2.3. Heel Effect
  - 11.3. Acquisition Systems
    - 11.3.1. Screen/Film
    - 11.3.2. Digital

- 11.3.3. Dual-Energy
- 11.3.4. Linear Tomography
- 11.3.5. Tomosynthesis
- 11.4. Image Characteristics
  - 11.4.1. Spatial and Contrast Resolution
  - 11.4.2. Body-Part and View-Specific Processing
  - 11.4.3. CAD/Diagnosis
- 11.5. Application Requirements
  - 11.5.1. Chest
  - 11.5.2. Abdomen
  - 11.5.3. Spine
  - 11.5.4. Extremities
  - 11.5.5. Bone Densitometry (DEXA)
  - 11.5.6. Pediatrics
  - 11.5.7. Portable
- 11.6. Dose and Dosimetry
  - 11.6.1. Entrance Skin Exposure
  - 11.6.2. Dose for Different Applications
  - 11.6.3. Technique Optimization
- 11.7. Technical Assessment and Equipment Purchase Recommendations
- 11.8. Quality Control (QC) Tests and Frequencies
- 11.9. Guidelines
- 12. **Mammography**
  - 12.1. Clinical Importance
    - 12.1.1. Screening
    - 12.1.2. Diagnosis and Detection Requirements
    - 12.1.3. Attenuation Characteristics of Breast Tissue and Lesions
  - 12.2. Spectrum Requirements
    - 12.2.1. Anode Material
    - 12.2.2. kVp
    - 12.2.3. Filtration
    - 12.2.4. HVL
  - 12.3. Geometrical Requirements
    - 12.3.1. Focal Spot Size
    - 12.3.2. Collimation
    - 12.3.3. Beam Central Axis
    - 12.3.4. Chest-Wall Coverage
    - 12.3.5. Heel Effect
    - 12.3.6. Grid
    - 12.3.7. Magnification
  - 12.4. Acquisition Systems
    - 12.4.1. Screen/Film
    - 12.4.2. Full-Field Digital Mammography
    - 12.4.3. Stereotactic Biopsy Systems
    - 12.4.4. Tomosynthesis
  - 12.5. Compression

- 12.6. Magnification Mode
  - 12.6.1. Use
  - 12.6.2. Small Focal Spot
  - 12.6.3. Air Gap
- 12.7. Dose
  - 12.7.1. Average Glandular Dose
  - 12.7.2. Dosimetry
  - 12.7.3. AEC
  - 12.7.4. Technique Optimization
- 12.8. Digital Image Processing
  - 12.8.1. Skin Equalization
  - 12.8.2. Advanced Proprietary Processing
  - 12.8.3. CAD/Diagnosis
- 12.9. MQSA Regulations
  - 12.9.1. Responsibilities of Physician, Technologist and Physicist
  - 12.9.2. Dose
  - 12.9.3. Image Quality/Accreditation Phantom
  - 12.9.4. QC Tests and Frequencies
- 12.10. American College of Radiology (ACR) Accreditation
- 12.11. Technical Assessment and Equipment Purchase Recommendations
- 13. Fluoroscopy/Interventional**
  - 13.1. System Components
    - 13.1.1. Tube
    - 13.1.2. Filtration
    - 13.1.3. Collimation
    - 13.1.4. Grids
    - 13.1.5. Automatic Brightness Control (ABC)
    - 13.1.6. Automatic Brightness Stabilization (ABS)
    - 13.1.7. Compensation Filters (semi-transparent)
  - 13.2. Geometry
    - 13.2.1. Focal Spot Size
    - 13.2.2. Magnification
    - 13.2.3. Under-Table vs. Over-Table X-Ray Tube
  - 13.3. Image Intensifier (II) Acquisition Systems
    - 13.3.1. II Structure
    - 13.3.2. Minification Gain
    - 13.3.3. Brightness Gain
    - 13.3.4. Field of View (FOV), Magnification, and Resolution
    - 13.3.5. Camera and Video System
  - 13.4. Flat-panel Acquisition Systems
    - 13.4.1. Detectors
    - 13.4.2. Magnification
    - 13.4.3. Binning
    - 13.4.4. Comparison to II
  - 13.5. Real-time Imaging
    - 13.5.1. Continuous Fluoroscopy

- 13.5.2. High-Dose Rate Fluoroscopy
- 13.5.3. Variable Frame Rate Pulsed Fluoroscopy
- 13.5.4. Spot Film (digital and film)
- 13.5.5. Effective mA as a Function of Mode
- 13.5.6. Variable Beam Filtration as a Function of Mode
- 13.5.7. Software Processing as a Function of Mode
- 13.6. Image Degradations
  - 13.6.1. Lag
  - 13.6.2. Contrast Ratio and Veiling Glare
  - 13.6.3. Distortion
  - 13.6.4. Spatial and Contrast Resolution
- 13.7. Image Processing
  - 13.7.1. Frame Averaging
  - 13.7.2. Temporal Recursive Filtering
  - 13.7.3. Last Image Hold
  - 13.7.4. Edge Enhancement/Smoothing
  - 13.7.5. Digital Subtraction Angiography (DSA)
  - 13.7.6. Road Mapping
- 13.8. Application Requirements
  - 13.8.1. Contrast Imaging (e.g., Iodine, barium)
  - 13.8.2. Cine
  - 13.8.3. C-Arms
- 13.9. Clinical Applications
  - 13.9.1. Conventional Fluoroscopy (e.g., GI, GU)
  - 13.9.2. Interventional
  - 13.9.3. DSA
  - 13.9.4. Bi-Plane
  - 13.9.5. Cardiac
  - 13.9.6. Pediatric
- 13.10. Dose and Dosimetry
  - 13.10.1. FDA and State (where applicable) Dose Rate Limits
  - 13.10.2. Dose-Area-Product (DAP) Meters
  - 13.10.3. Entrance Skin Exposure
  - 13.10.4. Patient Dose for Various Acquisition Modes
  - 13.10.5. Patient Size
  - 13.10.6. Operator and Staff Dose
  - 13.10.7. Operator, Staff and Caregiver Shielding and Protection Considerations
  - 13.10.8. Technique Optimization
- 13.11. Image Quality
  - 13.11.1. Low-Contrast Resolution
  - 13.11.2. High-Contrast Resolution
  - 13.11.3. Temporal Resolution
- 13.12. Regulations
  - 13.12.1. Five-Minute Timer
  - 13.12.2. Minimum Source to Patient Distance
  - 13.12.3. Sentinel Event

- 13.13. Technical Assessment and Equipment Purchase Recommendations
- 13.14. QC Tests and Frequencies
- 13.15. Guidelines
- 14. **Computed Tomography (CT)**
  - 14.1. System Components
    - 14.1.1. System Geometry
    - 14.1.2. Tube
    - 14.1.3. Bow-Tie Filters
    - 14.1.4. Added Filtration
    - 14.1.5. Collimation
    - 14.1.6. Data Acquisition System
    - 14.1.7. Detector Types and Arrays
  - 14.2. System Types
    - 14.2.1. Third Generation
    - 14.2.2. Electron-Beam
    - 14.2.3. Dual Source
    - 14.2.4. Cone-Beam
  - 14.3. Image Acquisition Parameters
    - 14.3.1. kVp
    - 14.3.2. mAs/effective mAs
    - 14.3.3. Pitch (Collimator)
    - 14.3.4. Slice Thickness and Sensitivity Profile
    - 14.3.5. Detector Binning
  - 14.4. Image formation
    - 14.4.1. Filtered Projection
    - 14.4.2. Back-Projection
    - 14.4.3. Convolution Algorithms (Filters)
    - 14.4.4. Helical Reconstruction
    - 14.4.5. Linear Attenuation Coefficient
    - 14.4.6. Hounsfield Unit Definition
    - 14.4.7. Typical CT Numbers
  - 14.5. Modes of operation
    - 14.5.1. Axial and Helical Modes
    - 14.5.2. Fixed and Variable mA
    - 14.5.3. CT Fluoroscopy
    - 14.5.4. Localizer Image (Scout)
    - 14.5.5. Contrast CT
    - 14.5.6. Temporal CT / Perfusion
    - 14.5.7. Dual-Energy
    - 14.5.8. CT Angiography
  - 14.6. Image Characteristics and Artifacts
    - 14.6.1. Spatial and Contrast Resolution
    - 14.6.2. SNR vs. Acquisition Parameters
    - 14.6.3. Beam Hardening
    - 14.6.4. Motion
    - 14.6.5. Partial Volume

- 14.6.6. Incomplete Projection
- 14.6.7. Photon Starvation
- 14.6.8. Streak Artifacts
- 14.6.9. Ring Artifacts
- 14.7. Image Processing and Display
  - 14.7.1. Pre-Set Tissue Windows
  - 14.7.2. Multi-Planar Reconstruction (MPR)
  - 14.7.3. Maximum Intensity Projection (MIP)
  - 14.7.4. Volume and Surface Rendering
- 14.8. Clinical Application and Protocols
  - 14.8.1. Head
  - 14.8.2. Spine
  - 14.8.3. Thoracic
  - 14.8.4. Angiography
  - 14.8.5. Cardiac
  - 14.8.6. Abdomen
  - 14.8.7. Virtual Colonoscopy
  - 14.8.8. CT Fluoroscopy
  - 14.8.9. Whole-Body
  - 14.8.10. Pediatric
- 14.9. Dose and Dosimetry
  - 14.9.1. CT Dose Index (CTDI, etc.)
  - 14.9.2. Multiple Scan Average Dose (MSAD)
  - 14.9.3. Dose Length Product (DLP)
  - 14.9.4. Dose Profile
  - 14.9.5. Effective Dose
  - 14.9.6. Phantom Measurement Methods
  - 14.9.7. Dose for Different Application Protocols
  - 14.9.8. Technique Optimization
- 14.10. Technical Assessment and Equipment Purchase Recommendations
- 14.11. QC Tests and Frequencies
- 14.12. Guidelines
- 15. Ultrasound**
  - 15.1. Sound Wave Propagation
    - 15.1.1. Definition of Sound and Ultrasound
    - 15.1.2. Longitudinal Waves
    - 15.1.3. Transverse Waves
  - 15.2. Sound Wave Properties
    - 15.2.1. Wavelength, Frequency, Period and Velocity
    - 15.2.2. Density and Pressure Changes in Materials
    - 15.2.3. Particle Motion and Particle Velocity
    - 15.2.4. Compressibility and Bulk Modulus
    - 15.2.5. Dependence of Sound Speed on Medium and Properties
  - 15.3. Power and Intensity
    - 15.3.1. Decibel Scale
    - 15.3.2. Relationship between Intensity and Pressure

- 15.4. Interactions of Ultrasound with Matter
  - 15.4.1. Acoustic Impedance
    - 15.4.1.1. Relationship to Density, Speed and Compressibility
    - 15.4.1.2. Impedance in Tissues
  - 15.4.2. Attenuation
    - 15.4.2.1. Causes and Relationship to Sound Properties
    - 15.4.2.2. Attenuation Coefficient
    - 15.4.2.3. 0.5 dB/cm/MHz for Soft Tissue
  - 15.4.3. Reflection
    - 15.4.3.1. Role of Impedance
    - 15.4.3.2. Normal and Oblique Incidence
    - 15.4.3.3. Specular Reflection
    - 15.4.3.4. Diffuse Reflection
    - 15.4.3.5. Reflection Coefficient
  - 15.4.4. Transmission
  - 15.4.5. Refraction - Snell's Law
  - 15.4.6. Scattering
    - 15.4.6.1. Hyperechoic and Hypoechoic Regions
    - 15.4.6.2. Relationship to Frequency and Scatterer Size
    - 15.4.6.3. Rayleigh Scattering
- 15.5. Transducer Components
  - 15.5.1. Piezoelectric Materials
    - 15.5.1.1. Composition
    - 15.5.1.2. Piezoelectric Reception and Transmission
    - 15.5.1.3. Physical and Electrical Properties
    - 15.5.1.4. Resonance Frequency and Crystal Thickness
  - 15.5.2. Transducer Construction
    - 15.5.2.1. Electronics
    - 15.5.2.2. Matching Layers
    - 15.5.2.3. Capacitive Micromachined Ultrasonic Transducers (C-MUT) Transducers
- 15.6. Transducer Arrays
  - 15.6.1. Linear and Curvilinear Arrays
  - 15.6.2. Phased Arrays
  - 15.6.3. Annular Arrays
  - 15.6.4. 1.5D and 2D Arrays
- 15.7. Beam properties
  - 15.7.1. The Near Field
  - 15.7.2. The Far Field
  - 15.7.3. Focused Transducers
  - 15.7.4. Side and Grating Lobes
- 15.8. Transducer Array Beam Formation and Focusing
  - 15.8.1. Linear and Sector Scanning
  - 15.8.2. Transmit Focusing
  - 15.8.3. Receive Focusing
  - 15.8.4. Beam Steering

- 15.8.5. Beam Shaping
- 15.9. Resolution
  - 15.9.1. Axial
  - 15.9.2. Lateral
  - 15.9.3. Elevational (slice thickness)
  - 15.9.4. Temporal
- 15.10. Pulse-Echo Imaging
  - 15.10.1. Method
  - 15.10.2. Timing
    - 15.10.2.1. Pulse-Repetition Frequency
    - 15.10.2.2. Pulse-Repetition Period
  - 15.10.3. Field of View/Maximum Depth
  - 15.10.4. Frame Rate
- 15.11. Image Data Acquisition
  - 15.11.1. Signal Acquisition
  - 15.11.2. Pre-amplification and Analog to Digital Conversion
  - 15.11.3. Time Gain Compensation
  - 15.11.4. Logarithmic Compression
  - 15.11.5. Demodulation and Envelope Detection
  - 15.11.6. Rejection
  - 15.11.7. Processed Signal
- 15.12. Image Processing and Display
  - 15.12.1. Display Modes
    - 15.12.1.1. A-Mode
    - 15.12.1.2. B-Mode
    - 15.12.1.3. M-Mode
  - 15.12.2. Scan Converter
  - 15.12.3. Image Frame Rate Dependencies
    - 15.12.3.1. Depth Setting
    - 15.12.3.2. Transmit Focal Zones
    - 15.12.3.3. Sector Size and Line Density
  - 15.12.4. Image Display
    - 15.12.4.1. Preprocessing and Post-processing
    - 15.12.4.2. Speckle and Speckle Reduction
    - 15.12.4.3. Read Zoom and Write Zoom
  - 15.12.5. Distance, Area and Volume Measurements
  - 15.12.6. Compound Imaging
- 15.13. Ultrasound Contrast Agents
- 15.14. Harmonic Imaging
  - 15.14.1. Nonlinear Propagation and Origin of Harmonics
  - 15.14.2. Formation of Harmonics in Ultrasound
  - 15.14.3. Features of Harmonic Imaging
    - 15.14.3.1. Resolution Improvements
    - 15.14.3.2. Side-Lobe Interference
    - 15.14.3.3. Artifact Reduction
  - 15.14.4. Discrimination of Fundamental and Harmonic Frequencies

- 15.14.5. Narrow-Band Harmonic Imaging
- 15.14.6. Pulse-Inversion Harmonic Imaging
- 15.15. Special Purpose Transducer Assemblies
  - 15.15.1. Intra-Cavitary Transducers
  - 15.15.2. Catheter-Mounted
    - 15.15.2.1. Rotating Single-Element Transducers
    - 15.15.2.2. Phased Array Transducers
- 15.16. Three-Dimensional (3D) Imaging
  - 15.16.1. Image Reconstruction
  - 15.16.2. Transducer Registration Methods
    - 15.16.2.1. Free-Form Motion with External Localizers
    - 15.16.2.2. Free-Form Motion without External Localizers
    - 15.16.2.3. Externally Driven Mechanical
    - 15.16.2.4. Mechanical 3-D transducers
    - 15.16.2.5. 2-D Arrays
  - 15.16.3. Extended View Imaging
  - 15.16.4. Time-Dependent Imaging (4D)
- 15.17. Artifacts
  - 15.17.1. Refraction
  - 15.17.2. Shadowing and Enhancement
  - 15.17.3. Reverberation
  - 15.17.4. Speed Displacement
  - 15.17.5. Comet Tail
  - 15.17.6. Side and Grating Lobes
  - 15.17.7. Multipath Reflection and Mirror Image
  - 15.17.8. Range Ambiguity
- 15.18. Doppler Ultrasound
  - 15.18.1. Doppler Theory
  - 15.18.2. Doppler-Frequency Shift
    - 15.18.2.1. Reflector Velocity Dependence
    - 15.18.2.2. Doppler Angle Dependence
  - 15.18.3. Spectral Analysis
  - 15.18.4. Continuous Wave (CW) Doppler
  - 15.18.5. Pulsed Doppler
    - 15.18.5.1. Pulse Transmission and Range Gating
    - 15.18.5.2. Aliasing
  - 15.18.6. Duplex Scanning
  - 15.18.7. Color Flow Imaging
  - 15.18.8. Power Doppler
- 15.19. Technical Assessment and Equipment Purchase Recommendations
- 15.20. Quality Control and Test Frequency
- 15.21. Guidelines
- 15.22. Safety and Bioeffects
  - 15.22.1. Mechanisms for Producing Bioeffects
    - 15.22.1.1. Heating
    - 15.22.1.2. Cavitation

- 15.22.1.3. Direct Mechanical
- 15.22.2. Acoustic power
  - 15.22.2.1. Variation with Focus and Output Setting
  - 15.22.2.2. Pulse Repetition Frequency
  - 15.22.2.3. Transducer Frequency
  - 15.22.2.4. Operation Mode
- 15.22.3. Intensity Measures of Pulsed Ultrasound
  - 15.22.3.1. Spatial Average/Temporal Average Intensity [I(SATA)]
  - 15.22.3.2. Spatial Peak /Temporal Average Intensity [I(SPTA)]
  - 15.22.3.3. Spatial Peak/Pulse Average Intensity [I(SPPA)]
  - 15.22.3.4. Spatial Peak/Temporal Peak Intensity [I(SPTP)]
- 15.22.4. Real-time Acoustical Output Labeling
  - 15.22.4.1. Thermal Index (TI)
  - 15.22.4.2. Mechanical Index (MI)
- 16. Magnetic Resonance**
  - 16.1. Magnetism and Magnetic Fields
    - 16.1.1. Magnetic Susceptibility
    - 16.1.2. Type of Magnetic Materials
    - 16.1.3. Magnetic Fields (B)
      - 16.1.3.1. Units for B
      - 16.1.3.2. Magnetic Dipole
      - 16.1.3.3. Magnetic Moment
      - 16.1.3.4. Nuclear Magnetism (protons and biologically relevant nuclei)
    - 16.1.4. Magnetic Moment Interaction with an External Field ( $B_0$ )
      - 16.1.4.1. Alignment (low-energy/high-energy states)
      - 16.1.4.2. Precession
      - 16.1.4.3. Larmor Equation
    - 16.1.5. Net Magnetization Due to  $B_0$ 
      - 16.1.5.1. Longitudinal Magnetization ( $M_z$ )
      - 16.1.5.2. Transverse Magnetization ( $M_{xy}$ )
      - 16.1.5.3. Proton Density (Spin-Density)
      - 16.1.5.4. Field Strength Dependence
  - 16.2. Nuclear Magnetic Resonance and Excitation
    - 16.2.1. Radiofrequency (RF) field ( $B_1$ )
    - 16.2.2. Flip Angle RF Pulse
    - 16.2.3. Free-Induction Decay (FID)
    - 16.2.4.  $90^\circ/180^\circ$  RF Pulses
  - 16.3. Spin Density
  - 16.4.  $T_2$  (Spin-Spin or Transverse) Relaxation
    - 16.4.1. Intrinsic Spin-Spin Interactions
    - 16.4.2. Transverse Magnetization Decay
    - 16.4.3. Typical Tissue  $T_2$  Values
  - 16.5.  $T_2^*$  Relaxation
    - 16.5.1. Dependence on Field Inhomogeneity
    - 16.5.2. Susceptibility-Induced Dephasing (e.g., tissue-air interfaces)
  - 16.6.  $T_1$  (Spin-Lattice or Longitudinal) Relaxation

- 16.6.1. Spin-Lattice Interactions
- 16.6.2. Longitudinal Recovery
- 16.6.3. Typical Tissue  $T_1$  values
- 16.6.4. Field-Strength Dependence
- 16.7. Contrast Mechanisms (Pulse Sequences)
  - 16.7.1. Spin Echo (SE) Pulse Sequence
    - 16.7.1.1. Pulse Sequence Basics (Timing Diagrams)
    - 16.7.1.2. Echo Time (TE)
    - 16.7.1.3. Repetition Time (TR)
    - 16.7.1.4. SE Signal Intensity Dependence on TE and TR
    - 16.7.1.5. SE Contrast ( $T_1$ , Proton density,  $T_2$ -weighted)
  - 16.7.2. Inversion Recovery Pulse Sequence
    - 16.7.2.1. Inversion Time (TI)
    - 16.7.2.2. Short-Time ( $\tau$ ) Inversion Recovery (STIR)
    - 16.7.2.3. Fluid-Attenuated Inversion Recovery (FLAIR)
  - 16.7.3. Gradient Echo Pulse Sequence
    - 16.7.3.1. Basic Advantages/Disadvantages Compared to SE Sequence
    - 16.7.3.2. Gradient-Echo Signal-Intensity and Effect of Flip Angle
    - 16.7.3.3. RF-Pulse Spoiling
    - 16.7.3.4. Gradient Echo Contrast ( $T_2^*/T_1$ ,  $T_2^*$ , and  $T_1$  – weighting)
- 16.8. MR instrumentation
  - 16.8.1. Static Magnetic Field ( $B_0$ ) Systems
  - 16.8.2. Gradient Field Subsystem
    - 16.8.2.1. Gradient Coil Geometry (x,y and z)
    - 16.8.2.2. Gradient Strength (mT/m)
    - 16.8.2.3. Eddy Currents and Effects on Gradient Performance
    - 16.8.2.4. Compensation for Effects of Eddy Currents
    - 16.8.2.5. Slew-Rate Specification (mT/m/s)
  - 16.8.3. Shim Coils
    - 16.8.3.1. Inhomogeneity Compensation
    - 16.8.3.2. Passive and Active
    - 16.8.3.3. Geometry
  - 16.8.4. RF Transmitter ( $B_1$ ) Subsystem
    - 16.8.4.1. RF-Pulse Bandwidth
    - 16.8.4.2. Control of Flip Angle
  - 16.8.5. RF Receiver Subsystem
    - 16.8.5.1. Digital Sampling of Received Signals
    - 16.8.5.2. Receive Bandwidth
    - 16.8.5.3. Parallel (Phased-Array) Receive Channels
  - 16.8.6. RF Coils
    - 16.8.6.1. Transmit-and-Receive Coils
    - 16.8.6.2. Volume vs. Surface Coils
    - 16.8.6.3. Receive-Only Coils
    - 16.8.6.4. Quadrature vs. Linear Coils
    - 16.8.6.5. Birdcage Coils
    - 16.8.6.6. Phased-Array Coils

- 16.8.6.7. SENSE Coils
- 16.8.7. Data acquisition
  - 16.8.7.1. Analog-to-Digital Converter (ADC) Sampling
  - 16.8.7.2. Other Data Acquisition Elements
- 16.9. Image Acquisition
  - 16.9.1. Slice-Selection Gradient (SSG)
  - 16.9.2. Phase-Encoding Gradient (PEG)
  - 16.9.3. Frequency-Encoding Gradient (FEG)
- 16.10. Specifications of Pulse Sequences
  - 16.10.1. Acquisition Time Calculations
  - 16.10.2. Multi-Slice Acquisition
  - 16.10.3. Timing Diagrams of Common Pulse Sequences
    - 16.10.3.1. Spin-Echo/Multi-Echo
    - 16.10.3.2. Inversion Recovery
    - 16.10.3.3. Gradient Echo
    - 16.10.3.4. Multi-Planar
    - 16.10.3.5. Fast- or Turbo-Spin-Echo (FSE/TSE)
    - 16.10.3.6. Echo-Planar Imaging (EPI)
    - 16.10.3.7. Volume Imaging (3D)
- 16.11. Two-dimensional Fourier Transform (2DFT) Image Reconstruction
  - 16.11.1.  $k$ -Space Description
  - 16.11.2. Methods of “Filling  $k$ -Space”
    - 16.11.2.1. Rectangular
    - 16.11.2.2. Spiral
    - 16.11.2.3. Radial
    - 16.11.2.4. Fractional (e.g., Propeller, One-Half NEX, etc.)
- 16.12. Image Characteristics
  - 16.12.1. Factors Affecting Spatial Resolution
    - 16.12.1.1. Field-of-View (FOV)
    - 16.12.1.2. Pixel Size
    - 16.12.1.3. Slice Thickness
    - 16.12.1.4. Image Matrix Size
  - 16.12.2. Factors Affecting Signal-to-Noise Ratio (SNR)
    - 16.12.2.1. Voxel Size
    - 16.12.2.2. Signal Averages
    - 16.12.2.3. Receiver (Sampling) Bandwidth
    - 16.12.2.4. Magnetic Field Strength
    - 16.12.2.5. Slice “Cross-Talk”
    - 16.12.2.6. Reconstruction Algorithms
    - 16.12.2.7. RF Coil Quality Factor
    - 16.12.2.8. Pulse Sequence Specific Effects
  - 16.12.3. Tradeoffs among Spatial Resolution, SNR, and Acquisition Time
  - 16.12.4. Factors Affecting Image Contrast
    - 16.12.4.1. Proton Density,  $T_1$ ,  $T_2$
    - 16.12.4.2. Susceptibility
- 16.13. Contrast Agents

- 16.13.1. Paramagnetic
- 16.13.2. Superparamagnetic
- 16.13.3. Susceptibility Agents
- 16.14. Saturation
  - 16.14.1. Spatial
  - 16.14.2. Chemical (e.g., fat, silicone)
- 16.15. Special Acquisition Techniques
  - 16.15.1. Angiography
    - 16.15.1.1. Effect of Blood Flow on Signal Intensity
    - 16.15.1.2. Time-of-Flight (2D/3D) Techniques
    - 16.15.1.3. Phase-Contrast Techniques
    - 16.15.1.4. Contrast-Agent Enhanced MRA Techniques
  - 16.15.2. Diffusion Imaging
    - 16.15.2.1. Basic Principles
    - 16.15.2.2. Diffusion-Weighted Imaging (DWI) Techniques
    - 16.15.2.3. Apparent Diffusion Coefficient (ADC)
    - 16.15.2.4. Diffusion Tensor Imaging (DTI) Techniques
  - 16.15.3. Functional MRI (fMRI)
    - 16.15.3.1. Blood Oxygen Level Dependent (BOLD) Principles
    - 16.15.3.2. Clinical Applications
  - 16.15.4. Magnetization Transfer Contrast (MTC)
    - 16.15.4.1. Basic Principles
    - 16.15.4.2. Contrast Mechanisms
    - 16.15.4.3. Clinical Applications
  - 16.15.5. Parallel MRI
    - 16.15.5.1. Basic Principles
    - 16.15.5.2. Image-Based Implementation
    - 16.15.5.3. *k*-Space-Based Implementation
  - 16.15.6. Spectroscopy
    - 16.15.6.1. Basic Principles
    - 16.15.6.2. Single Voxel Techniques
    - 16.15.6.3. Chemical-Shift Imaging (CSI), 2D and 3D
    - 16.15.6.4. Water Suppression
    - 16.15.6.5. Importance of TE and TR Values
    - 16.15.6.6. Clinical Applications
- 16.16. Artifacts
  - 16.16.1. Metal and Susceptibility Artifacts
  - 16.16.2. Gradient Field and Static Field Inhomogeneity Artifacts
  - 16.16.3. Radiofrequency Artifacts
  - 16.16.4. *k*-Space Errors
  - 16.16.5. Motion Artifacts
  - 16.16.6. Chemical Shift Artifacts (Fat/Water)
  - 16.16.7. Gibbs (Ringing, Truncation) Artifacts
  - 16.16.8. Aliasing (Wraparound)
  - 16.16.9. Partial-Volume Artifacts
  - 16.16.10. High Speed Imaging Artifacts (e.g., Echo-Planar Distortion, Ghosting)

- 16.16.11. Effect of High Field Strength on Artifacts
- 16.17. Image Processing and Display
  - 16.17.1. Maximum-Intensity Projection (MIP)
  - 16.17.2. Volume-/Surface-Rendering
- 16.18. Safety and Bioeffects
  - 16.18.1. Static Magnetic Field
    - 16.18.1.1. Biological Effects
    - 16.18.1.2. Projectile Hazards
    - 16.18.1.3. Effects on Implanted Devices
    - 16.18.1.4. FDA Limits
  - 16.18.2. RF Field
    - 16.18.2.1. Biological Effects, Including Tissue Heating
    - 16.18.2.2. RF Heating of Conductors and Potential Burns
    - 16.18.2.3. Specific Absorption Rate (SAR)
    - 16.18.2.4. Problems with High Field Strength Systems
    - 16.18.2.5. FDA Limits
  - 16.18.3. Gradient Field
    - 16.18.3.1. Biological Effects, Including Peripheral Nerve Stimulation
    - 16.18.3.2. Sound Pressure Level (“Noise”) Issues and Limits
    - 16.18.3.3. FDA Limits
  - 16.18.4. Contrast Agent Safety Issues
  - 16.18.5. Screening of Patients and Healthcare Workers
  - 16.18.6. MR Safety Systems (including superconducting magnet “quench” systems)
  - 16.18.7. Cryogenic Materials
- 16.19. Magnet System Siting
  - 16.19.1. Basic Facility Design (including “zone” design)
  - 16.19.2. Magnetic Fringe Field and the 0.5 mT (5G) Line
  - 16.19.3. Magnetic Field Shielding
  - 16.19.4. RF Field Shielding
  - 16.19.5. Effects of MRI on Other Equipment/Objects
  - 16.19.6. Effects of Equipment/Objects on MRI
- 16.20. Technical Assessment and Equipment Purchase Recommendations
- 16.21. QC tests and frequencies
- 16.22. Guidelines
- 17. Nuclear Medicine**
  - 17.1. Radionuclide Decay
    - 17.1.1. Radioactivity
      - 17.1.1.1. Definition
      - 17.1.1.2. Units
      - 17.1.1.3. Decay Constant
      - 17.1.1.4. Decay Equation
      - 17.1.1.5. Half-Life (Physical, Biological, and Effective)
    - 17.1.2. Nuclear Transformation
      - 17.1.2.1. N/Z Ratio and Nuclear Stability
      - 17.1.2.2. Beta (negative electron) Decay
      - 17.1.2.3. Positron (positive electron) Decay

- 17.1.2.4. Electron Capture
- 17.1.2.5. Isomeric Transition
- 17.1.2.6. Alpha Decay
- 17.1.2.7. Internal Conversion
- 17.1.3. Radioactive Equilibrium
  - 17.1.3.1. Transient
  - 17.1.3.2. Secular
- 17.1.4. Nuclear Fission
- 17.1.5. Nuclear Fusion
- 17.2. Radioisotope Production
  - 17.2.1. Accelerator/Cyclotron
  - 17.2.2. Reactor
    - 17.2.2.1. Fission Products
    - 17.2.2.2. Neutron-Activation Products
  - 17.2.3. Radionuclide Generators
    - 17.2.3.1.  $^{99}\text{Mo} - ^{99\text{m}}\text{Tc}$
    - 17.2.3.2. Other (e.g.  $^{82}\text{Sr} - ^{82}\text{Rb}$  PET)
    - 17.2.3.3. Quality Control
  - 17.2.4. Radiopharmaceuticals
    - 17.2.4.1. Preparation of Radiopharmaceuticals
    - 17.2.4.2. Mechanisms of Localization
    - 17.2.4.3. Uptake and Decay
    - 17.2.4.4. Quality Control
- 17.3. Radiation Detection Instrumentation
  - 17.3.1. Gas-filled Detectors
    - 17.3.1.1. Mechanisms of Operation
    - 17.3.1.2. Applications and Limitations
    - 17.3.1.3. Survey Meters (e.g., GM Counter, Ionization Chamber)
    - 17.3.1.4. Dose Calibrator
    - 17.3.1.5. Quality Control
  - 17.3.2. Scintillation Detectors
    - 17.3.2.1. Mechanisms of Operation
    - 17.3.2.2. Applications and Limitations
    - 17.3.2.3. Pulse-Height Spectroscopy
    - 17.3.2.4. Thyroid Probe
    - 17.3.2.5. Well Counter
    - 17.3.2.6. Survey Meter
    - 17.3.2.7. Quality Control
  - 17.3.3. Semi-Conductor Detectors
    - 17.3.3.1. Mechanisms of Operation
    - 17.3.3.2. Applications and Limitations
    - 17.3.3.3. Pulse-height Spectroscopy
  - 17.3.4. Thermoluminescent Dosimeters (TLDs)
    - 17.3.4.1. Mechanisms of Operation
    - 17.3.4.2. Applications and Limitations
  - 17.3.5. Optically-Stimulated Luminescent (OSL) Dosimeters

- 17.3.5.1. Mechanisms of Operation
- 17.3.5.2. Applications and Limitations
- 17.4. Scintillation Camera
  - 17.4.1. Clinical Purpose
  - 17.4.2. Camera Design
    - 17.4.2.1. Crystal Parameters
    - 17.4.2.2. Spatial Localization
    - 17.4.2.3. Energy Discrimination
  - 17.4.3. Collimators
    - 17.4.3.1. Parallel Hole
    - 17.4.3.2. Pinhole
    - 17.4.3.3. Sensitivity
    - 17.4.3.4. Resolution
  - 17.4.4. Image Acquisition
    - 17.4.4.1. Static
    - 17.4.4.2. Dynamic
    - 17.4.4.3. Gated
    - 17.4.4.4. List-Mode
  - 17.4.5. Image Processing
    - 17.4.5.1. Subtraction
    - 17.4.5.2. Region of Interest (ROI)
    - 17.4.5.3. Time-Activity Curves
    - 17.4.5.4. Spatial Filtering
    - 17.4.5.5. Temporal Filtering
  - 17.4.6. Measures of Performance
    - 17.4.6.1. Uniformity
    - 17.4.6.2. Spatial Resolution
    - 17.4.6.3. Energy Resolution
    - 17.4.6.4. Spatial Linearity
    - 17.4.6.5. Sensitivity
    - 17.4.6.6. Count-Rate Performance
    - 17.4.6.7. Patient Parameters
  - 17.4.7. Artifacts
    - 17.4.7.1. Damaged or Broken Crystal
    - 17.4.7.2. Non-Uniformity
    - 17.4.7.3. Bad Phototube
    - 17.4.7.4. Improper Energy Peaking
    - 17.4.7.5. Mechanical Separation of Coupling Elements
    - 17.4.7.6. Damaged Collimators
    - 17.4.7.7. Motion
  - 17.4.8. Clinical Examples
    - 17.4.8.1. Thyroid
    - 17.4.8.2. Bone
    - 17.4.8.3. Renal
    - 17.4.8.4. Liver/Spleen
    - 17.4.8.5. Cardiac (Ejection Fraction, Myocardial Perfusion)

- 17.4.8.6. Ventilation Perfusion (VQ)
- 17.4.8.7. Multi-Energy Imaging
- 17.4.8.8. Tumor Imaging
- 17.4.9. Procedure Types (Alternate to Above)
  - 17.4.9.1. Adult
  - 17.4.9.2. Pediatric
  - 17.4.9.3. Infant
  - 17.4.9.4. Pregnant Patient
  - 17.4.9.5. Breast-Feeding Patient
- 17.4.10. Technical Assessment and Equipment Purchase Recommendations
- 17.5. SPECT Imaging
  - 17.5.1. Clinical Purpose
  - 17.5.2. Mechanisms of Operation
    - 17.5.2.1. Single- and Multi-Head Units
    - 17.5.2.2. Rotational Arc
    - 17.5.2.3. Continuous Motion
    - 17.5.2.4. Step-and-Shoot
    - 17.5.2.5. Non-Circular Orbits
  - 17.5.3. Attenuation Correction
  - 17.5.4. Image Reconstruction
  - 17.5.5. Sensitivity and Resolution
  - 17.5.6. Technical Assessment and Equipment Purchase Recommendations
  - 17.5.7. Quality Control
  - 17.5.8. Artifacts
    - 17.5.8.1. Attenuation
    - 17.5.8.2. Center of Rotation
    - 17.5.8.3. Uniformity
    - 17.5.8.4. Stray Magnetic Field Effects
    - 17.5.8.5. Motion
  - 17.5.9. Clinical Examples
- 17.6. Positron Emission Tomography (PET)
  - 17.6.1. Clinical Purpose
  - 17.6.2. Mechanisms of Operation
  - 17.6.3. Detector
    - 17.6.3.1. Type
    - 17.6.3.2. Configuration
  - 17.6.4. Coincidence Detection
  - 17.6.5. Time-of-Flight
  - 17.6.6. Attenuation Correction
  - 17.6.7. Standardized Uptake Value (SUV)
  - 17.6.8. 2D vs. 3D Operation
  - 17.6.9. Count Rate / Administered Dose Considerations
  - 17.6.10. Image Reconstruction
  - 17.6.11. Sensitivity and Resolution
  - 17.6.12. Technical Assessment and Equipment Purchase Recommendations
  - 17.6.13. Quality Control

- 17.6.14. Artifacts
  - 17.6.14.1. Attenuation Correction
  - 17.6.14.2. Motion
- 17.6.15. Clinical Examples
- 17.7. Combined Modalities
  - 17.7.1. SPECT/CT
    - 17.7.1.1. Mechanisms of Operation
    - 17.7.1.2. Clinical Applications
    - 17.7.1.3. Quality Control
    - 17.7.1.4. Artifacts
  - 17.7.2. PET/CT
    - 17.7.2.1. Mechanisms of Operation
    - 17.7.2.2. Clinical Applications
    - 17.7.2.3. Quality Control
    - 17.7.2.4. Artifacts

## Appendix A Committee Members

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## **Appendix B** History and general comments about intent of curriculum

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

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

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

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

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