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FOURTH EDITION

RADIOLOGY SECRETS Plus

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We would like to dedicate this book to our parents, who have supported us all the way and have made it possible for us to be where we are today; to our siblings, who have always encouraged us; to our spouses and children who bring joy and meaning to each day; and to all those who study and apply the art and science of radiology to do good for the patients entrusted to our care.

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PREFACE

Radiology is an essential component of current medical practice, having assumed a central role in the evaluation and follow-up of many clinical problems, from the head to the toes. Becoming familiar with and knowledgeable about the indications and capabilities of various diagnostic and therapeutic procedures that are driven by imaging, across a wide range of clinical subspecialties and imaging modalities, is important for those who use radiology for any diagnostic and therapeutic purpose. We have endeavored to create a practical and interesting book that distills the essential aspects of imaging for each subspecialty of radiology.

Whether you are a trainee (medical student, resident, or fellow), a physician in practice (in radiology, nuclear medicine, or another medical specialty), or another type of health care provider, this book was written for you.

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We would like to thank our friends and colleagues E. Scott Pretorius, MD, and Jeffrey A. Solomon, MD, MBA, the two prior co-editors of *Radiology Secrets*, for the opportunity to serve as editors for the latest edition of this book. We would also like to thank all of the contributing authors for helping to make this book a reality; without their expertise, there would be no such book.

TOP 100 RADIOLOGY SECRETS

1. Radiography is an imaging technique that uses x-rays to create images of a region of interest in the body; these images are projectional 2D images. Ultrasonography (US) is an imaging technique that uses high-frequency ultrasound waves to create images in real time. Computed tomography (CT) is an imaging technique that uses x-rays to create tomographic images. Magnetic resonance imaging (MRI) is an imaging technique that uses magnetism and radiofrequency waves to create tomographic images. Planar scintigraphy, single photon emission computed tomography (SPECT), and positron emission tomography (PET) are the nuclear medicine molecular imaging techniques available. They are used to image the distribution and accumulation of an administered radiotracer in organs/tissues of the body; the spatial distribution and amount of accumulation depend on the properties of the radiotracer and the disease states present in the involved organs.
2. Density, echogenicity, attenuation, and signal intensity are the descriptors of how bright or dark tissues are on radiography, US, CT, and MR images, respectively. Standardized uptake value (SUV) is a quantitative measure of PET radiotracer uptake in a tissue of interest.
3. If fluid has very high signal intensity on an MR image, then the image is likely T2-weighted. If fluid has low signal intensity on an MR image, then the image is likely T1-weighted. An easy reference organ is the signal intensity of cerebrospinal fluid on MR images; if it is bright, then the image is likely a T2-weighted image.
4. Quantitative radiology (QR) is the quantitative assessment of both normal and disease states using medical images in order to evaluate the severity, degree of change, and status of abnormal disease states relative to normal. This involves the development, standardization, and optimization of image acquisition protocols, computer-aided visualization and analysis (CAVA) methods, and reporting structures. CAVA provides quantitative information about objects of interest within digital images and involves use of image preprocessing, visualization, manipulation, and analysis.
5. A biomarker (biologic marker) is a characteristic that is objectively measured and evaluated as an indicator of normal biologic processes, pathogenic processes, or pharmacologic responses to a therapeutic intervention. Imaging biomarkers are obtained from image analysis.
6. Spatial resolution is the ability to display two separate but adjacent objects as distinct on an image. Contrast resolution is the ability to display tissues with different intensities as having distinct shades of gray on an image.
7. The picture archiving and communication system (PACS) is used to store and display medical images.
8. Distinguishing physiologic from allergic-like contrast reactions is important, as patients with physiologic reactions do not require future corticosteroid premedication, whereas those with allergic-like reactions may need future corticosteroid premedication.
9. Intravascular gadolinium-based contrast material is contraindicated for use in pregnant patients. However, iodinated contrast material can be administered to pregnant or potentially pregnant patients when needed for diagnostic purposes.
10. Dose optimization is often summarized as ALARA (“as low as reasonably achievable”), but it dictates that the radiologic examination should be tailored to the clinical question, patient size, and anatomy of interest.
11. Diagnostic mammography is indicated for women with a specific breast-related problem that needs to be evaluated. Screening mammography is indicated for asymptomatic patients.
12. Indications for breast MRI include evaluation for presence of breast cancer in the high-risk patient; evaluation of the extent of disease with a new breast cancer diagnosis; detection of an occult primary tumor in the presence of axillary disease; evaluation of silicone breast implant integrity; response monitoring of a known breast cancer to chemotherapy; and further diagnostic evaluation after an inconclusive mammographic and sonographic work-up.

13. On a frontal chest radiograph, the right atrium comprises the right heart border, whereas the aortic knob, main pulmonary artery, left atrial appendage, and left ventricle comprise the left heart border from superior to inferior. On a lateral chest radiograph, the left atrium comprises the posterior-superior heart border, whereas the right ventricle comprises the anterior heart border.
14. The most common cardiac or paracardiac mass is thrombus. The most common primary cardiac neoplasm is myxoma. The most common malignant neoplasm of the heart and pericardium is metastatic disease.
15. An aortic dissection is caused by a tear of the intima, creating a false channel or lumen within the wall of the aorta, which usually extends longitudinally within the aorta. Dissections involving the ascending aorta (Stanford type A and DeBakey types 1 and 2) are surgical emergencies, whereas descending aortic dissections are usually treated medically.
16. Cardiac CT provides not only accurate evaluation for coronary artery luminal stenosis with high sensitivity and specificity, but also valuable information about atherosclerotic plaque in the vessel wall.
17. An acute pulmonary embolus typically appears as a centrally located hypoattenuating filling defect within the pulmonary artery on CT. A chronic pulmonary embolus typically appears as an eccentrically located hypoattenuating filling defect within the pulmonary artery and may be associated with calcification, intraluminal bands or webs, decreased luminal caliber, or increased bronchial arterial collateral vessels.
18. Atherosclerosis is the most common cause of renal artery stenosis, most often occurs in older adults, and typically involves the proximal third of the renal artery. Fibromuscular dysplasia (FMD) is the second most common cause of renal artery stenosis, most often occurs in young or middle-aged women, and typically involves the distal third of the renal artery.
19. Be aware of the major blind spots on frontal chest radiography where nodules and masses are easily overlooked: the lung apices where the clavicles and ribs overlap, the hilar regions where vascular structures abound, the retrocardiac region, and the lung bases where there is superimposition with the upper abdominal soft tissue.
20. If you see lobar or segmental atelectasis on chest radiography, particularly without air bronchograms, be suspicious of an obstructive endobronchial lesion such as a lung cancer, and, at the minimum, get a short-term follow-up chest radiograph. If a pulmonary opacity does not resolve over time despite treatment with antimicrobial agents, be suspicious of a potential lung cancer.
21. Opacity is a nonspecific descriptor that implies a region that attenuates x-rays to a greater degree than surrounding tissues, and it can be due to any abnormality overlying or within the lung. Consolidation, however, specifically refers to an alveolar filling process, which opacifies the lung.
22. Imaging findings of reactivation tuberculosis (TB) may include upper lung zone predominant focal consolidation or nodular opacities, areas of cavitation, centrilobular, acinar, and/or tree-in-bud nodular opacities, interstitial miliary nodules, bronchiectasis, and thoracic lymphadenopathy (often with areas of central necrosis). When these findings are seen on imaging, alert the referring physician to the possibility of active TB.
23. Interstitial pulmonary edema, usually caused by congestive heart failure, is the most common interstitial abnormality encountered in daily practice.
24. Thymoma is the most common primary tumor of the anterior mediastinum and of the thymus. Neurogenic tumor is the most common mass of the posterior mediastinum.
25. If a pneumothorax is seen on chest radiography that is associated with contralateral mediastinal shift and inferior displacement of the ipsilateral hemidiaphragm, it is very worrisome for a tension pneumothorax. The physician caring for the patient must be notified immediately as emergent treatment is usually required to decompress the pneumothorax to prevent rapid death.
26. If a nasogastric tube, orogastric tube, or feeding tube is seen to extend into a distal bronchus, lung, or pleural space, the clinical staff should be notified immediately, and the radiologist should suggest that tube removal be performed only after a thoracostomy tube set is at the bedside in case a significant pneumothorax develops.
27. When air embolism is suspected during line placement or use, the patient should immediately be placed in the left lateral position to keep the air trapped in the right heart chambers, supplemental oxygen should be administered, and vital signs should be monitored.
28. Linear pneumatosis is highly suggestive of bowel ischemia.

29. Single-contrast gastrointestinal (GI) examinations use “thin barium” or water-soluble contrast material (no gas used) and are easier to perform in sick patients who cannot turn to detect bowel obstruction, perforation, or fistulas. Double-contrast GI examinations are more sensitive than single-contrast examinations for detecting mucosal abnormalities and use high-density barium and air/carbon dioxide, but they require patients to turn into different positions to coat the entire bowel, which can prove to be challenging for sick and debilitated patients.
30. Wall (mural) thickening is the hallmark of GI tract pathology. In general, the greater the degree of mural thickening, the more likely that malignancy is the underlying etiology. Asymmetric wall thickening and focal wall thickening are also features suggestive of malignancy.
31. The “target” sign, also known as mural stratification, is highly specific for the diagnosis of nonneoplastic disease when encountered in the small or large bowel. However, this specificity for nonneoplastic disease does not hold when it is encountered in the stomach.
32. Most hepatic lesions are hypointense relative to liver parenchyma on T1-weighted images. Lesion isointensity on T1-weighted images suggests that it is of hepatocellular origin.
33. On T2-weighted images, malignant hepatic lesions tend to have similar signal intensity as the spleen, whereas hepatic cysts and hemangiomas are hyperintense relative to the spleen and remain hyperintense on heavily T2-weighted images.
34. Metastatic disease to a cirrhotic liver is extremely rare. A focal hepatic lesion in a cirrhotic liver that either demonstrates arterial phase enhancement or isointensity to spleen on T2-weighted images is considered as hepatocellular carcinoma (HCC) until proven otherwise.
35. MRI has higher sensitivity than CT for the detection and localization of calculi within the gallbladder and biliary tree.
36. A splenic laceration is associated with a history of trauma, is irregular or branching in configuration, and is associated with adjacent areas of fluid, whereas a developmental splenic cleft is smooth without presence of surrounding fluid.
37. Pancreatic adenocarcinoma is generally unresectable when there is encasement of the mesenteric vasculature, invasion of organs other than the duodenum, or presence of distant metastatic disease.
38. Whenever you see visceral pelvic fat stranding on CT or MRI in a woman with an acute abdomen or pelvis, always consider the diagnosis of early pelvic inflammatory disease (PID) and notify the clinical team. This will allow them to definitively establish or exclude the diagnosis of PID and to implement therapy as needed to prevent future complications of PID.
39. Whenever you see findings of bowel obstruction on CT or MRI, always evaluate the etiology at the transition zone, and exclude the presence of a closed loop obstruction which constitutes a true surgical emergency.
40. If you visualize imaging findings of active arterial extravasation of contrast material, shock, or abdominal aortic aneurysm (AAA) rupture on CT or MRI, immediately check on the status of the patient, start resuscitative measures if needed, and get help from your clinical colleagues right away.
41. The anterior urethra in men is better evaluated on retrograde urethrography (RUG). The posterior urethra in men is better evaluated on voiding cystourethrography (VCUG).
42. An enhancing renal mass that does not contain macroscopic fat is considered to be secondary to renal cell carcinoma (RCC) until proven otherwise. Cystic renal lesions that contain thick or irregular walls, thick or irregular internal septations, or solid nodular components with enhancement are considered as suspicious for cystic RCC until proven otherwise. Presence of macroscopic fat within a renal mass is diagnostic of a renal angiomyolipoma (AML).
43. Most adrenal incidentalomas are benign in nature, and the most commonly detected incidental adrenal lesion is a nonhyperfunctional adrenal adenoma. Presence of microscopic lipid content within a small (≤3 cm in size) homogeneous adrenal gland nodule is essentially diagnostic of an adrenal adenoma. Presence of macroscopic fat within an adrenal gland nodule or mass is characteristic of an adrenal myelolipoma. Adrenal gland nodules/masses which have a large size (>4-5 cm), grow over time, are heterogeneous in appearance, or have irregular margins are more likely to be malignant in etiology.
44. Retroperitoneal tumors are usually malignant and are most commonly due to lymphoma, retroperitoneal sarcoma, and metastatic disease.

45. Septate uterus is the most common type of congenital uterine anomaly. Leiomyoma, or fibroid, is the most common neoplasm of the female genitourinary tract.
46. Most intratesticular masses are malignant, whereas most extratesticular scrotal masses are benign. Spermatoceles and epididymal cysts are the most common causes of a scrotal mass.
47. The imaging modality of choice for a patient with acute head trauma is an unenhanced brain CT scan.
48. Time is BRAIN. Rapid diagnosis of ischemic stroke and prompt initiation of treatment are critical for a good outcome. Diffusion-weighted imaging (DWI) is the most sensitive MRI sequence for detection of acute stroke.
49. An epidural hematoma has a biconvex lenticular shape, is contained by dural sutures, and is associated with temporal bone or other skull fractures. Large hematomas are treated promptly with clot evacuation to prevent brain herniation and associated complications. A subdural hematoma is crescentic in shape, is not contained by dural sutures but does not cross the falx or tentorium, and may or may not be associated with a skull fracture.
50. The most common primary intra-axial brain tumor in adults is glioblastoma multiforme. The most common posterior fossa/infratentorial neoplasm in adults is a metastasis. The most common extra-axial tumor in adults is meningioma.
51. MRI is the modality of choice for evaluating suprahyoid neck lesions, whereas infrahyoid neck lesions are imaged first with CT. CT is the imaging modality of choice for conductive hearing loss. MRI is the imaging modality of choice in adult-onset sensorineural hearing loss.
52. The most common cause of a cystic neck mass in an adult is metastatic lymphadenopathy.
53. The best predictor of acute sinusitis in the appropriate clinical setting (facial pain, nasal drainage, fever) is the presence of an air-fluid level on a CT scan.
54. Fatigue fractures are the result of abnormal stresses on normal bone, whereas insufficiency fractures are the result of normal stresses on abnormal bone.
55. The most common type of shoulder dislocation is anterior, whereas the most common type of hip dislocation is posterior.
56. A fat-fluid level seen in a joint space in the setting of trauma is due to a lipohemarthrosis and is indicative of an intraarticular fracture.
57. Osteoporosis is characterized by diminished bone density with otherwise normal bone architecture, whereas osteomalacia (in adults) and rickets (in children) are characterized by normal bone density in the setting of abnormal quality of bone. Both may manifest as osteopenia (i.e., diffusely increased lucency of bone) on radiography or CT.
58. Subperiosteal bone resorption is a pathognomonic radiographic sign of hyperparathyroidism. A Looser zone fracture is a pathognomonic radiographic sign of osteomalacia.
59. Metastatic calcification is due to alterations in calcium or phosphorus metabolism, whereas dystrophic calcification is due to tissue injury.
60. A large complex joint effusion with thick synovial enhancement and periarticular bone marrow edema raises suspicion for septic arthritis, particularly when only one joint is involved. Periarticular osteopenia, uniform joint space narrowing, osseous erosions, and soft tissue swelling are also suggestive imaging features of septic arthritis. However, whenever this diagnosis is suspected clinically, it should be confirmed or excluded by joint aspiration.
61. Necrotizing fasciitis is a surgical emergency, requiring prompt diagnosis and treatment. Its diagnosis, while primarily clinical, also rests in the identification of soft tissue emphysema. Other suggestive imaging features include fascial plane thickening, edema, or enhancement, as well as edema, phlegmon, or abscess formation in subjacent muscles.
62. Tennis elbow (lateral epicondylitis) and golfer's elbow (medial epicondylitis) are due to inflammation of the common extensor and common flexor tendons, respectively.
63. Ligament and tendon injuries are seen as full- or partial-thickness high signal intensity foci in the normally low signal structures on T2-weighted images.
64. MRI is the examination of choice for evaluation of suspected hip fractures when radiography fails to reveal the cause of hip pain, because it is a highly sensitive and specific modality for detection of radiographically occult fractures and is more sensitive than CT for detection of other possible causes of hip pain such as soft tissue injuries.

65. A meniscal tear is present when either abnormal signal intensity within a meniscus extending to the articular surface on two contiguous slices or abnormal meniscal morphology is visualized.
66. Ankle inversion occurs much more commonly than ankle eversion and results in injury to the anterior talofibular ligament, calcaneofibular ligament, and posterior talofibular ligament in sequence.
67. For a viable intrauterine gestation, an embryo should be visible sonographically by a mean gestational sac diameter of 25 mm, and an embryonic heart rate should be detected by a crown-rump length of 7 mm.
68. The most common sonographic finding of an ectopic pregnancy is an adnexal mass.
69. Sonographic features of thyroid nodules that are associated with a higher risk of malignancy include microcalcifications, coarse and dystrophic calcifications, marked hypoechogenicity, infiltrative and/or microlobulated margins, and taller-than-wide shape. Sonographic features associated with a very low risk of malignancy are a nearly entirely cystic nodule and a spongiform appearance in a nodule under 2 cm without marked vascularity, calcifications, or irregular margins.
70. Proper equipment and qualified personnel should be readily available prior to administration of conscious sedation to any patient.
71. The basic life support sequence of steps for patient resuscitation (C-A-B) includes assessment of **C**irculation (heart rate and blood pressure), establishment of an **A**irway, and assessment of **B**reathing (ventilation).
72. In most cases, inferior vena cava (IVC) filters should be placed below the lowest renal vein when possible.
73. AAA rupture is often fatal; AAAs must therefore be detected, monitored, and treated prior to rupture. Intervention is typically indicated when the aneurysm reaches 5.5 cm, although many clinicians treat at the 5 cm threshold.
74. Transarterial chemoembolization (TACE) is a liver-directed therapy for liver tumors, including HCC, hepatic metastases, and occasionally hepatic adenomas. Radiofrequency ablation (RFA) is a technique for generating heat and subsequent coagulation necrosis in living tissues through alternating electrical currents and is used to treat many conditions, including liver, kidney, bone, and lung tumors.
75. Embolization on both sides of a pseudoaneurysm, aneurysm, or arteriovenous fistula (AVF) is necessary to prevent reconstitution of flow via collaterals, which causes lesion recurrence.
76. An obstructed, infected biliary system constitutes a medical emergency.
77. Benign biliary strictures tend to taper gradually with smooth borders, whereas malignant biliary strictures tend to occur abruptly, often with irregular borders.
78. Urosepsis is an indication for emergent percutaneous nephrostomy (PCN).
79. ^{18}F-fluoro-2-deoxy-2-D-glucose (FDG) PET imaging is useful for lesion characterization, tumor staging and pretreatment planning, clinical outcome prognostication, tumor response assessment, and tumor restaging. FDG PET changes management in up to 40% of patients with cancer, most often due to detection of distant metastases.
80. Focal FDG uptake in the uterus or adnexa of a postmenopausal woman, in the thyroid gland, or in the bowel is generally considered as suspicious for malignancy until proven otherwise. Lower levels of FDG uptake within tumors generally reflect a more indolent tumor biology and portend a more favorable clinical outcome. A reduction in tumor FDG uptake after therapy is more likely to be associated with a histopathologic response and improved patient survival than is a lack of change.
81. Any cause of increased bone turnover, including primary malignant bone tumors, osseous metastases, osteoid osteoma, osteomyelitis, trauma, degenerative change, metabolic bone disease, and Paget's disease, may lead to increased radiotracer uptake in bone on a bone scan or ^{18}F-sodium fluoride (^{18}F-NaF) PET scan.
82. A "superscan" occurs when there is diffusely increased radiotracer uptake in the bones and is most commonly seen with widespread osseous metastatic disease, metabolic bone disease, or widespread Paget's disease.
83. Visualization of one or more wedge-shaped perfusion scan defects, segmental or subsegmental in distribution, unmatched to any finding on a ventilation scan or chest radiograph is suspicious for pulmonary embolism (PE).

84. Hot nodules on radioiodine thyroid scintigraphy are most often benign, whereas cold nodules may be due to thyroid cancer.
85. A GI bleeding scan is useful to detect and localize sites of active hemorrhage in the bowel and is considered as positive when there is a focus of growing radiotracer activity that moves through the bowel.
86. A reversible (or transient) defect on stress myocardial perfusion imaging (SMPI) occurs when there is a lack of myocardial perfusion during stress but normal myocardial perfusion during rest, and it implies coronary artery disease (CAD) with coronary artery stenosis of at least 70%. A nonreversible (or fixed) defect on SMPI occurs when there is a lack of myocardial perfusion during both stress and rest, and it implies scarring, such as from prior myocardial infarction, or chronically ischemic but viable hibernating myocardium.
87. Symmetric hypometabolism in the bilateral temporoparietal regions of the brain is a classic finding observed on FDG PET imaging in patients with Alzheimer's disease.
88. Seizure foci have increased perfusion and metabolism on ictal cerebral blood flow (CBF) and FDG PET brain scans, respectively, whereas decreased perfusion and metabolism may be observed on interictal scans.
89. The dose-limiting toxicity of most radiopharmaceutical therapies is bone marrow suppression.
90. The epiglottis should be triangular or flat in configuration on lateral neck radiography. Recognition of a bulbous or thumblike appearance of the epiglottis indicates acute epiglottitis, which is a medical emergency.
91. Croup, or acute laryngotracheobronchitis, is characterized by symmetric subglottic narrowing on frontal neck radiography leading to the "steeple" sign due to edema of the subglottic tissues.
92. Tetralogy of Fallot is the most common cyanotic congenital heart disease (CHD) of childhood and has four characteristic features: right ventricular outflow tract obstruction, an overriding aorta, a ventricular septal defect (VSD), and right ventricular hypertrophy.
93. A malignant or "interarterial" course of an anomalous coronary artery between the aortic root and pulmonary arterial trunk may lead to extrinsic compression of the artery, potentially resulting in sudden death.
94. Necrotizing enterocolitis (NEC) predominantly occurs in premature infants and may manifest as diffuse gaseous distention of bowel, loss of the normal symmetric bowel gas pattern, persistent focal dilation of bowel, ascites, pneumatosis intestinalis, portal venous gas, or pneumoperitoneum on abdominal radiography. When pneumoperitoneum develops, this is a definite sign of bowel perforation, necessitating surgical intervention.
95. An ingested coin in the esophagus is typically visualized en face on a frontal chest radiograph, whereas an aspirated coin in the trachea is typically visualized end-on on a frontal chest radiograph.
96. When there is complete duplication of the kidney, the Weigert-Meyer rule states that the lower pole ureter inserts normally into the bladder at the trigone, whereas the upper pole ureter inserts ectopically into the bladder medial and caudal to the lower pole ureteral insertion site.
97. The most common solid renal mass in infants is fetal renal hamartoma, also known as mesoblastic nephroma, and the most common childhood abdominal malignancy is Wilms tumor. The most common primary pediatric bone tumors are Ewing sarcoma and osteosarcoma.
98. The usual sequence of ossification of the secondary ossification centers of the elbow can be remembered by the mnemonic CRITOE: **C**apitellum (1 year), **R**adial head (3 years), **I**nternal (medial) epicondyle (5 years), **T**rochlea (7 years), **O**lecranon (9 years), and **E**xternal (lateral) epicondyle (11 years).
99. Metaphyseal corner fractures or bucket-handle fractures have high specificity for child abuse. Posterior rib fractures, fractures of the scapula, spinous process, or sternum, vertebral compression fractures, complex skull fractures, and multiple fractures of different ages are suggestive of child abuse as well. Subdural hematomas, particularly when interhemispheric or seen in the posterior fossa/tentorial locations, are suspicious for head trauma related to shaken infant syndrome.
100. The legal requirements for a finding of malpractice are establishment of physician-patient relationship; breach of the duty of care, or negligence; adverse outcome with injury or harm; and direct causality between negligence and outcome. The most common reasons that radiologists are sued are failure to diagnose; failure to communicate findings in an appropriate and timely manner; and failure to suggest the next appropriate procedure.

RADIOLOGY SECRETS PLUS

INTRODUCTION TO RADIOGRAPHY, FLUOROSCOPY, AND TOMOSYNTHESIS

Drew A. Torigian, MD, MA, FSAR

CHAPTER 1

RADIOGRAPHY

1. **What is radiography?**
   Radiography is an imaging technique that uses x-rays to create projectional (2D) images of a region of interest in the body. It is performed by shining x-rays on a film or other image detector with a patient placed in front of it in a certain orientation. Different types of tissues in the patient attenuate x-rays to different degrees, leading to formation of a composite of x-ray shadows that will ultimately create the radiographic image. It is most commonly used to evaluate the bones and joints, the chest (especially the lungs), the abdomen and pelvis (especially the bowel), and the breasts (in which case it is called mammography).

2. **When were x-rays discovered?**
   Wilhelm Conrad Roentgen is credited with the discovery of x-rays in 1895, and was the first to systematically study them. He was also the first to obtain an x-ray photograph of part of the human body, his wife's hand, discovering its potential medical use. In 1901, he received the first Nobel Prize in physics. X-rays are sometimes referred to as Roentgen rays.

3. **How do x-rays differ from other types of electromagnetic radiation?**
   X-rays have higher energies, higher frequencies, and shorter wavelengths in the electromagnetic spectrum than ultraviolet light, visible light, infrared light, microwaves, and radio waves, and lower energies, lower frequencies, and longer wavelengths than gamma rays. Diagnostic x-rays typically have energies between 20 and 150 keV.

4. **How do x-rays interact with matter?**
   X-rays may either pass through matter unaffected, may be absorbed, or may be scattered (the latter of which leads to decreased image quality). Key factors that influence which interactions occur include the incident x-ray photon energy and the physical density, thickness, and atomic number of the material being imaged.

5. **What is an x-ray tube?**
   An x-ray tube is a device that is used to create x-rays for diagnostic imaging. It contains a negatively charged cathode that contains a filament (usually made of coiled tungsten wire) to produce electrons. The electrons are accelerated toward a positively charged anode that contains a target (usually made of tungsten or made of molybdenum and rhodium in mammography) where x-rays are produced. Both the cathode and anode are housed within a vacuum tube.

6. **How are x-rays for diagnostic imaging produced?**
   In the x-ray tube, about 90% of x-rays are created when electrons emitted from the cathode pass close to positively charged atomic nuclei within the anode target and change direction, resulting in a loss of energy in the form of x-ray photons known as bremsstrahlung ("braking") x-rays. An additional 10% of x-rays are produced when inner shell atomic electrons of the anode target are ejected by incident electrons, followed by relaxation of outer shell atomic electrons to fill the inner shell vacancies, leading to emission of energy in the form of x-ray photons known as characteristic x-rays.

7. **What is a focal spot?**
   A focal spot is the apparent source of x-rays in an x-ray tube. Smaller focal spots (such as those used in mammography) produce sharper images, whereas larger focal spots (such as those used in fluoroscopy) tolerate greater amounts of heat.

8. **What is a collimator?**
   A collimator is a device used to narrow the x-ray beam as it leaves the x-ray tube prior to entering the patient, reducing x-ray scatter and improving image contrast.

9. **What happens to most of the energy entering the x-ray tube?**
   Most (99%) of the energy is converted to heat, whereas about 1% is converted to x-rays.

10. **What key input parameters may be adjusted when generating x-rays?**
    The key parameters are the voltage applied across the x-ray tube (measured in kilovolts [kV]), the current flowing through the x-ray tube (measured in milliamperes [mA]), and the exposure time (measured in milliseconds [ms]). The

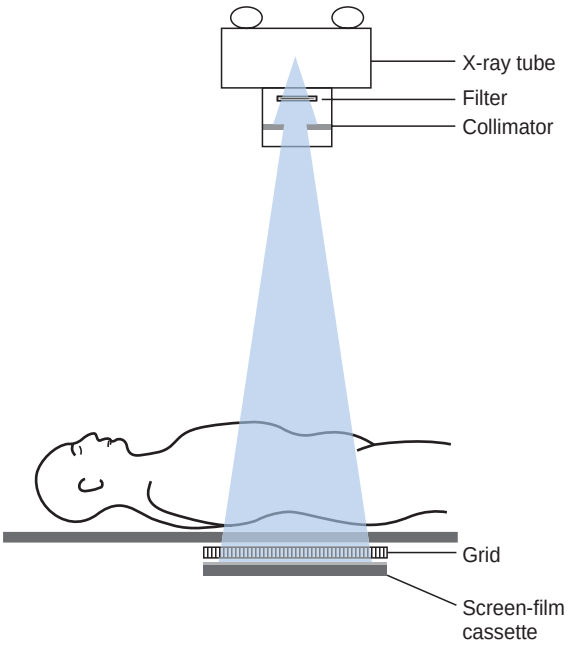

Figure 1-1. Schematic for apparatus used in screen film radiography.

product of tube current (in mA) and exposure time (in s) can be expressed in milliampere-seconds (mAs), which is directly proportional to x-ray tube output.

11. What are the effects of increasing kV?

X-ray peak and mean energies increase, penetration power increases, radiograph exposure increases, and image contrast (which primarily depends on kV) decreases.

12. What are the effects of increasing mAs?

X-ray exposure of a radiograph increases radiograph exposure. X-ray peak energy, mean energy, and penetration power do not change.

13. What is screen film radiography?

In screen film radiography (Figure 1-1), a sheet of film coated with a light-sensitive silver halide emulsion is placed in a light-tight cassette between two intensifying screens. The screens convert incident x-rays into visible light which then expose the film. The exposed film is then removed from the cassette, developed, and fixed to create a hardcopy radiograph.

14. What is computed radiography (CR)?

In CR, a photostimulable storage phosphor plate is used to transiently store a latent image following an x-ray exposure in the form of electrons trapped within the phosphor. This latent image is then extracted offline by a separate laser-based device that scans the plate to create a softcopy digital radiographic image that is stored electronically. CR eliminates the need to store hardcopy radiographic film and improves the ability to adjust the brightness and contrast of the digital image as needed.

15. What is digital radiography (DR)?

In DR (Figure 1-2), x-ray exposures upon a flat panel image detector are automatically processed into digital radiographic images in a fully integrated device without further user interaction.

16. What is dual energy radiography?

In dual energy radiography, two radiographic images of a patient are (nearly) simultaneously acquired at two different mean x-ray beam energies. These images are then combined to create a subtraction image to highlight either soft tissue or bone components present in the patient, as these components differentially attenuate the x-rays at different energies.

17. What is an anti-scatter grid?

An anti-scatter grid is a device, typically composed of narrow parallel strips of lead, that is placed between the patient and the image detector. It blocks scattered x-rays from reaching the film but allows nonscattered x-rays that pass from the x-ray tube and through the patient to reach the film, improving image contrast. The grid moves during the x-ray exposure, so that the grid is not visible on the radiographic image.

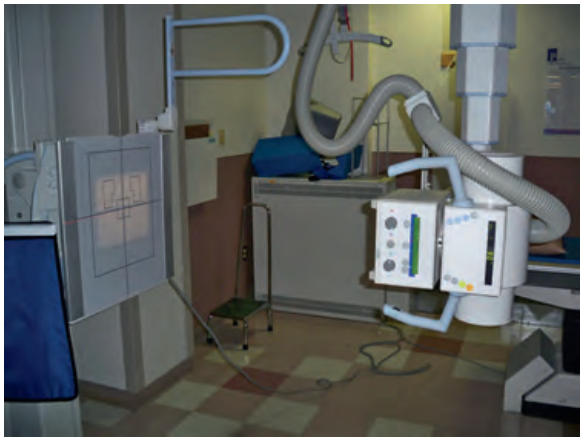

Figure 1-2. Typical DR unit with x-ray tube located on right and anti-scatter grid and flat panel detector located on left.

18. What is the inverse square law?

The x-ray beam intensity decreases with the square of the distance from the x-ray source. Thus, if the distance between oneself and an x-ray source is doubled, the x-ray exposure decreases by fourfold.

19. What is the difference between a posteroanterior (PA) and an anteroposterior (AP) radiograph?

These differ based on the direction of the x-ray beam passing through a patient. A PA radiograph occurs when the x-ray beam enters from the posterior aspect of the patient and exits anteriorly to reach the x-ray detector. An AP radiograph occurs when the x-ray beam enters from the anterior aspect of the patient and exits posteriorly to reach the x-ray detector.

20. What are the five basic densities seen on a radiograph?

These include air, fat, soft tissue, bone, and metal. Air appears black on a radiograph, because it minimally attenuates the x-ray beam. Bone appears white and metal appears even more white on a radiograph, because they both markedly attenuate the x-ray beam. Fat and soft tissue attenuate intermediate amounts of the x-ray beam and appear dark gray and brighter gray, respectively.

21. How does mammographic technique differ from that performed in chest and abdominal radiography?

A lower kV (for higher image contrast) and a higher mA (for a shorter exposure time) are used in mammography compared to those in radiography of the chest and abdomen.

FLUOROSCOPY

22. What is fluoroscopy?

Fluoroscopy is a projectional (2D) imaging technique that uses continuously emitted x-rays to perform real-time imaging of a patient. An x-ray tube in the fluoroscope (Figure 1-3) emits an x-ray beam that passes through the patient and falls upon an image intensifier. The image intensifier converts the x-ray radiation into visible light images and amplifies them. These images are then displayed on a monitor and can be viewed or recorded.

23. What are some clinical applications of fluoroscopy?

Fluoroscopy is commonly used to evaluate the gastrointestinal tract with esophagography, an upper gastrointestinal examination (to evaluate the stomach), a small bowel follow-through, or a barium enema (to evaluate the large bowel). It is also commonly used in interventional procedures such as arthrography, myelography, and angiography.

24. What general types of contrast agents are used in gastrointestinal fluoroscopic studies?

Barium sulfate is the standard oral contrast agent used for routine gastrointestinal fluoroscopic studies. More viscous suspensions are used for double-contrast (air and oral contrast) studies, whereas less viscous suspensions are used for single-contrast (oral contrast only) studies. When gastrointestinal tract perforation is suspected, a water-soluble contrast agent such as Gastrografin is instead utilized to prevent barium peritonitis, although it is contraindicated when there is a risk of aspiration because it may induce acute pulmonary edema.

25. What is digital subtraction angiography (DSA)?

DSA is a fluoroscopic imaging technique in which a precontrast digital mask image is subtracted from images acquired after intravascular contrast administration. This results in improved image contrast between contrast-enhanced vessels and background, because background structures such as bone and soft tissue do not enhance and are removed from the image.

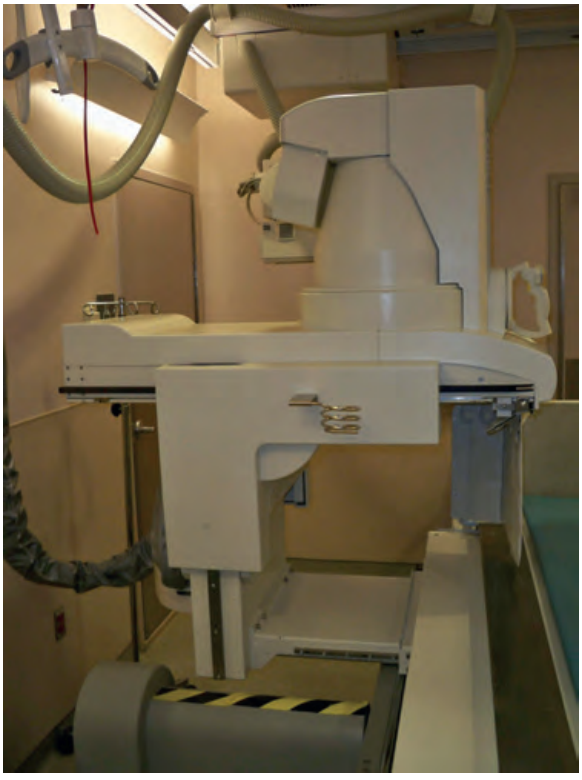

Figure 1-3. Typical fluoroscope with x-ray tube located on top.

TOMOSYNTHESIS

26. What is tomosynthesis, and how does it work?

Tomosynthesis is an x-ray-based imaging technique that is used to create high-resolution tomographic (cross-sectional) images of a region of interest in the body. It works by first acquiring multiple x-ray images of a patient from various angles with a digital flat panel detector and then using computer algorithms to reconstruct the data into tomographic images.

27. What are some clinical applications of tomosynthesis?

Tomosynthesis can be used to potentially improve the detection of breast cancer (particularly in women with dense breast tissue) compared to mammography and to improve the detection of small lung nodules in the chest compared to chest radiography.

KEY POINTS

- Radiography is an imaging technique that uses x-rays to create projectional (2D) images of a region of interest in the body.
- Fluoroscopy is a projectional (2D) imaging technique that uses continuously emitted x-rays to perform real-time imaging of a patient.
- Digital tomosynthesis is an x-ray-based imaging technique that is used to create high-resolution tomographic (cross-sectional) images of a region of interest in the body.
- Increasing kV increases the peak energy, mean energy, and penetration power of x-rays, increases radiograph exposure, and decreases image contrast.
- Increasing mAs increases the amount of x-rays produced, does not change x-ray energy or penetration power, and increases radiograph exposure.

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CHAPTER 2

INTRODUCTION TO ULTRASONOGRAPHY, CT, AND MRI

Drew A. Torigian, MD, MA, FSAR

ULTRASONOGRAPHY (US)

1. **What is ultrasonography (US), and how does it work?**
   US is a structural imaging technique that uses high-frequency mechanical ultrasound waves (with frequencies greater than audible sound waves) to create real-time tomographic (cross-sectional) images. A hand-held transducer is applied to a part of the body to transmit ultrasound waves into the patient. Reflected ultrasound waves (echoes) are then detected by the transducer and processed by a computer to create digital images that can be viewed or recorded (Figure 2-1).

2. **When was US first used for clinical diagnostic purposes?**
   US was first used as a clinical diagnostic imaging technique in 1942 by Karl Dussik to locate brain tumors and the cerebral ventricles.

3. **What are some common clinical applications of US?**
   US is often used for initial evaluation of the abdominal organs (e.g., to evaluate for acute cholecystitis and choledocholithiasis), the pelvic organs (e.g., to evaluate for uterine leiomyomas, ovarian torsion, ectopic pregnancy, endometrial abnormalities, prostate cancer, and testicular torsion), the vessels (e.g., to evaluate for carotid artery stenosis and femoral vein deep venous thrombosis), the thyroid and parathyroid glands (e.g., to assess for thyroid nodules and parathyroid adenomas), and the joints (e.g., to assess for rotator cuff tears) and to serve as a real-time imaging guide during percutaneous biopsies. As US does not involve the use of ionizing radiation, it is also used during pregnancy (e.g., to evaluate the embryo/fetus for congenital anomalies) and in the pediatric setting (e.g., to evaluate the brain and hip joints in infants).

4. **Why is gel used in US?**
   Gel is applied between the transducer and skin to displace air and minimize large reflections that would interfere with ultrasound transmission from the transducer into the patient and vice versa. Reflections tend to occur at tissue interfaces where there are large differences in the speed of propagation of ultrasound waves, such as at air/soft tissue and bone/soft tissue interfaces. Gel decreases such reflections at the skin surface by matching the acoustic impedances of the transducer surface and skin surface.

5. **What is a transducer, and what types are available for US?**
   A transducer (Figure 2-2) is an electronic device that is used to produce ultrasound waves for transmission into the patient and to receive reflected ultrasound waves (echoes) to create digital images. Lower-frequency ultrasound transducers have a greater depth of tissue penetration, whereas higher-frequency ultrasound transducers have a higher spatial resolution. For general abdominal US, which requires sufficient depth of penetration to image the liver, spleen, and pancreas, a 3- to 5-MHz transducer may be utilized. For US of superficial structures such as the thyroid gland or scrotum, a 10-MHz transducer is often used. Endovaginal transducers are commonly used for gynecologic and early pregnancy examinations, whereas endorectal probes are available for prostate gland examinations.

6. **What is echogenicity?**
   Echogenicity is the descriptor of how bright or dark a tissue is on a US image, which depends on whether ultrasound waves are reflected, refracted, attenuated, or transmitted by the tissue. Hyperechoic or echogenic tissues (including air and bone) appear bright, hypoechoic tissues appear dark gray, and anechoic tissues (such as fluid) appear black.

7. **What is posterior acoustic enhancement?**
   This is the appearance of increased echogenicity beyond a tissue due to the increased transmission of ultrasound waves, and it is most commonly seen with fluid-filled structures such as cysts or the gallbladder.

8. **What is posterior acoustic shadowing?**
   This is the appearance of markedly decreased echogenicity beyond a highly reflecting or absorbing tissue due to the lack of ultrasound wave transmission. This is most commonly due to air, bone, or calcification such as in gallstones. For this reason, US is not used to image air-filled or osseous structures.

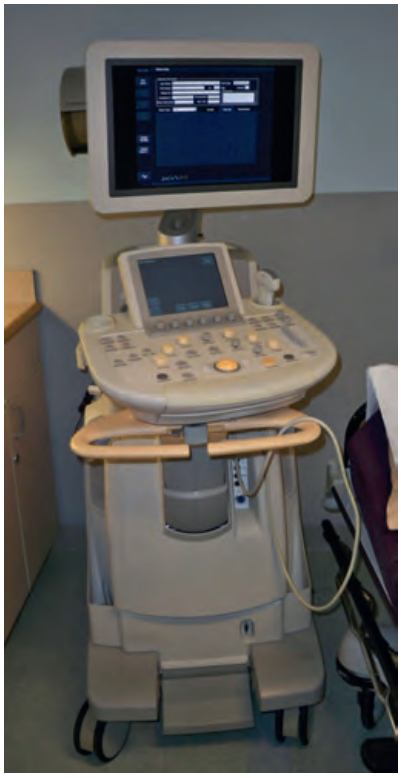

Figure 2-1. Typical mobile US unit with control panel and display monitor.

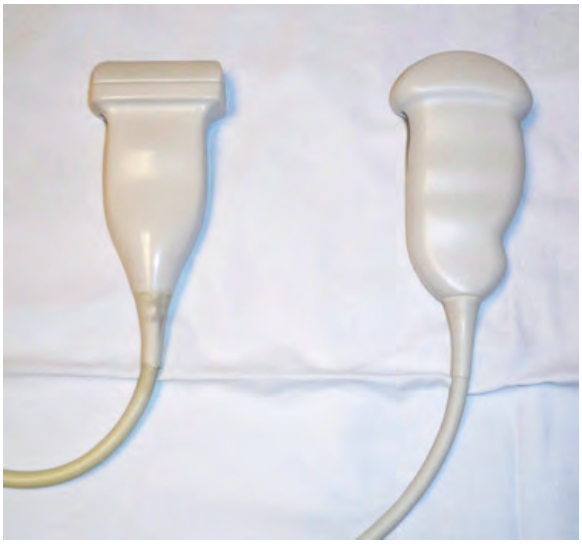

Figure 2-2. US transducers (linear on left, curved on right).

9. What is Doppler US?

Doppler US allows the imaging and quantification of blood flow velocity in vessels. It is based on the Doppler effect, which refers to the change in sound wave frequency and wavelength that occurs whenever the source of reflected waves (e.g., blood) is moving with respect to the detector (e.g., a transducer). Echoes from blood flowing toward a transducer will have higher frequencies and shorter wavelengths than blood flowing away from a transducer.

COMPUTED TOMOGRAPHY (CT)

10. What is computed tomography (CT), and how does it work?

CT is a structural imaging technique that uses x-rays to create tomographic (cross-sectional) images. A patient is placed onto a scanner table and passes through the CT gantry, which contains an x-ray tube and an oppositely located array of x-ray detectors that rotate together about the patient (Figure 2-3). A large number of x-ray projections are obtained from multiple angles at each slice position in the patient, each of which contains data regarding the differential attenuation of x-rays by different tissue types in the patient. These projections are then used by a computer to reconstruct CT images.

11. When was CT developed?

CT was developed in the late 1960s and early 1970s by Sir Godfrey Hounsfield in the United Kingdom at EMI Central Research Laboratories, and the first patient brain CT scan was obtained in 1971. Hounsfield, along with Allan Cormack, received the Nobel Prize in Physiology or Medicine in 1979.

12. What are some common clinical applications of CT?

CT is commonly used to evaluate patients with neoplastic, infectious, noninfectious inflammatory, and traumatic disorders and as a problem-solving tool to further characterize abnormalities detected on radiography or US. It is especially useful for evaluation of the lungs, airways, bowel, cortical bone, urothelial system, and vasculature.

13. What is multislice CT (MSCT)?

MSCT, also known as multidetector row CT (MDCT), uses x-ray detector arrays that have multiple rows of detector elements to acquire multiple simultaneous channels of data per x-ray beam rotation. This offers many advantages compared to single slice CT (SSCT), including faster scan times and the ability to generate CT images with submillimeter thickness, providing high-resolution images that are isotropic (i.e., composed of voxels that are cubic in

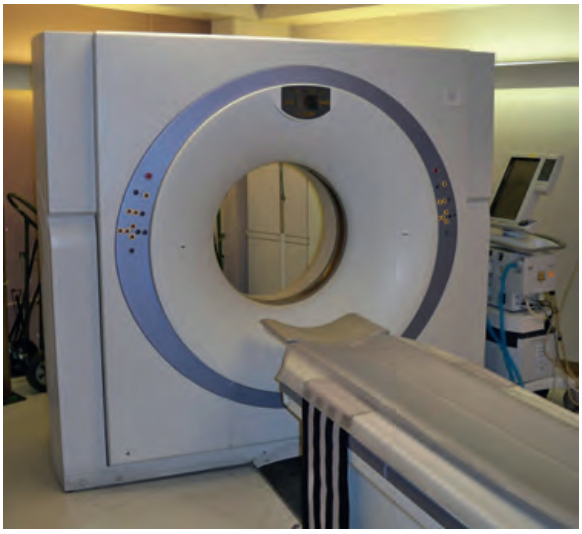

Figure 2-3. Typical MSCT scanner with CT gantry (which contains x-ray tube) and patient table.

shape). In essence, volumetric CT image data from a patient can now be acquired, and can then be reconstructed into 2D images in any plane of section and with any slice thickness desired. All modern CT scanners are MSCT scanners.

14. What is dual-source CT (DSCT)?

In DSCT, two x-ray tubes and two detector arrays located at 90-degree angles from one another are used in the CT gantry to acquire CT images. This improves the temporal resolution (i.e., acquisition speed) of the scanner and is mainly used in coronary CT studies to overcome cardiac motion artifacts during image acquisition.

15. What is dual-energy CT (DECT)?

In DECT, two sets of CT images are (nearly) simultaneously acquired at two different (low and high kilovoltage) mean x-ray beam energies. These images are then combined to create new images that highlight or suppress certain tissues of interest based on differential attenuation of the x-rays at different energies. For example, although iodine in contrast material and calcium in bone have similar high attenuation on standard CT images, the attenuation of iodine increases more markedly than calcium on low kilovoltage images relative to high kilovoltage images. Thus, new CT images demonstrating the contrast-enhanced vessels while suppressing surrounding bones can be created.

16. What is the difference between sequential and helical CT acquisition?

Sequential (or axial) CT acquisition is a step-and-shoot mode in which the patient table does not move during image acquisition of one or several slices at a time through the patient. Subsequently, the table advances and the process is repeated until the entire body region has been scanned. Helical (or spiral) CT acquisition is faster and involves continuous image acquisition while the patient table moves through the CT gantry. In this mode, the x-ray tube traces a helical trajectory around the patient. All modern CT scanners are helical scanners but can acquire images in sequential mode if desired.

17. What is attenuation?

Attenuation describes how bright or dark a tissue is on a CT image and is based on how much a tissue blocks (i.e., attenuates) the x-ray beam before reaching the x-ray detector. Attenuation of a tissue is predominantly determined by its atomic number (electron density) and physical density, although x-ray tube voltage also affects tissue attenuation. Every pixel (or voxel) on a CT image is assigned a gray scale value according to the mean attenuation of the tissue it corresponds to, which is called the CT number or relative attenuation coefficient. This is measured in Hounsfield units (HU), where pure water is the reference standard with an assigned CT number of 0 HU. Gas (–1000 HU) appears black, fat (–20 to –150 HU) appears dark gray, fluid (0 to 20 HU) appears gray, soft tissue (≈20 to 80 HU) appears bright gray, and bone, calcification, metal, and concentrated iodinated contrast material (≈150 to 1000 HU) appear white.

MAGNETIC RESONANCE IMAGING (MRI)

18. What is magnetic resonance imaging (MRI), and how does it work?

MRI is a structural and functional imaging technique that uses magnetism and radiofrequency (RF) waves to create tomographic (cross-sectional) images. A patient is placed into a scanner that contains a magnet that generates a very strong magnetic field (Figure 2-4). Atomic nuclei in the body, such as of hydrogen atoms, have a net magnetic moment and act like tiny magnets, aligning themselves with the main magnetic field. RF waves are turned on to knock the nuclear magnetic moments out of alignment. When the RF waves are then turned off, the nuclei realign themselves

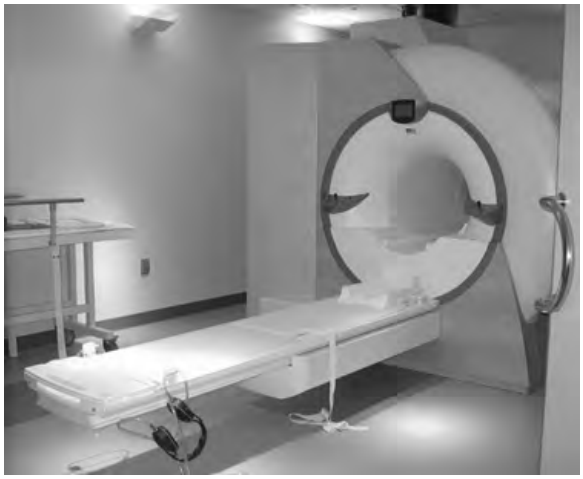

Figure 2-4. Typical MRI scanner with MRI gantry (which contains superconducting magnet) and patient table.

(i.e., relax) in the direction of the main magnetic field although at differential rates in different tissues. These differential relaxation rates lead to different signal properties of tissues that are detected by an RF coil placed around the patient. Magnetic gradients, controlled linear alterations of the magnetic field over distance in prespecified directions, are utilized to spatially localize the tissue signals so that MR images can be created. The process by which atomic nuclei undergo absorption or emission of RF energy is known as nuclear magnetic resonance (NMR).

19. When was MRI developed?

Isidor Rabi discovered the phenomenon of nuclear magnetic resonance in 1938 and received the Nobel Prize in Physics in 1944. Raymond Damadian discovered that the NMR signals of cancers appear different from those of normal tissues in 1971, proposed the concept of (and filed a patent for) the use of NMR for detecting cancer in the human body in 1972, and was the first to perform a human body MRI scan with the first full-body MRI scanner in 1977. In 1973, Paul Lauterbur produced the first tomographic MR image, and in 1976, Sir Peter Mansfield produced the first tomographic MR image of a human's finger. Lauterbur and Mansfield received the Nobel Prize in Physiology or Medicine in 2003.

20. What are some common clinical applications of MRI?

MRI is commonly used to evaluate patients with neoplastic, infectious, and noninfectious inflammatory disorders and as a problem-solving tool to further characterize abnormalities detected on radiography, US, CT, or PET/CT. It is especially useful for evaluation of the brain and spinal cord, breasts, heart and vasculature, abdominal and pelvic organs, and musculoskeletal soft tissue structures including the bone marrow, as it provides excellent soft tissue contrast. Because MRI does not involve the use of ionizing radiation, it is also used during pregnancy and in the pediatric setting.

21. What are some contraindications to the use of MRI?

In general, presence of metallic or electronic objects in the body such as orbital metallic foreign bodies, cerebral aneurysm clips, transvenous pacemakers, implantable cardioverter defibrillators, neurostimulators, and cochlear implants are contraindications for MRI, due to risks of device malfunction, device movement with tissue injury, or device heating with tissue injury. However, some patients with newer MRI-compatible versions of implanted metallic or electronic devices may be able to undergo MRI. A comprehensive website that provides updated information regarding the MRI safety of implants and devices is found at www.mrisafety.com. Claustrophobia is also a relative contraindication to MRI but can be alleviated by using patient sedation, a wide bore short length scanner, or an open field scanner. Pregnancy is not a contraindication to MRI, but it is a contraindication for use of gadolinium-based contrast material.

22. What is the typical field strength of magnets used in clinical MRI?

Magnetic field strengths of 0.5 to 3 Tesla (equivalent to 10,000 to 60,000 times the magnetic field strength of the Earth) are typically used in clinical MRI scanners, most often created by a superconducting magnet. Higher field strengths are desirable, as image signal-to-noise ratio (SNR) increases linearly with field strength, although there is a limit because the rate of energy deposition in tissue also increases with the square of field strength.

23. What are T1 and T2?

T1, the longitudinal relaxation time, is a measure of how long it takes atomic nuclei to realign longitudinally with the main magnetic field after they have been knocked over by an RF pulse. T2, the transverse relaxation time, is a measure of how long it takes a group of atomic nuclei that have been knocked over by an RF pulse to become maximally disordered in the transverse plane. Different tissues have different T1 and T2 times (usually on the order of

milliseconds [ms]), which form the basis for T1-weighted and T2-weighted MR image contrast, respectively. The T2 of a tissue is always less than its T1.

24. What is a pulse sequence?

A pulse sequence is a preprogrammed sequence of instructions regarding the timing, strength, and duration of RF pulses and magnetic gradients that are to be applied by the MRI scanner to create specific types of MR images. For example, pulse sequences can be created so that images are acquired slice by slice (2D) or volumetrically (3D) or are acquired during certain portions of the respiratory or cardiac cycles if desired. Image slice orientation, thickness, and spatial resolution can be adjusted, tissues of interest (such as fat or water) can be suppressed, and image contrast (or weighting) can be altered to accentuate other tissues of interest.

25. What is k space?

k space is a 2D graphical depiction of the digitized MR signal data required to create an MR image. Every point in k space contains information about every voxel in the MR image, and the inverse Fourier transform of k space creates the MR image.

26. What are TR and TE?

The repetition time (TR), the time to complete one full iteration of a pulse sequence, and the echo time (TE), the time between the start of a pulse sequence and the acquisition of data, are two parameters (usually reported in milliseconds [ms]) that are adjusted in a pulse sequence to change image contrast. TE is always shorter than TR.

27. What is a spin echo (SE) pulse sequence?

An SE pulse sequence begins with a 90-degree RF pulse (i.e., an RF pulse that flips atomic nuclei by 90 degrees), followed by a 180-degree RF pulse, leading to formation of an MRI signal called a spin echo. The pulse sequence is then repeated until enough spin echoes have been acquired to create MR images.

28. What is a fast spin echo (FSE) pulse sequence?

An FSE pulse sequence begins with a 90-degree RF pulse, followed by a series of 180-degree RF pulses, leading to formation of multiple spin echoes. Since multiple spin echoes are obtained at a time, fewer repetitions of the pulse sequences are required to create MR images, leading to faster image acquisition times. This pulse sequence is commonly used to obtain T2-weighted images and sometimes T1-weighted images.

29. What is a gradient recalled echo (GRE) pulse sequence?

A GRE pulse sequence begins with a <90-degree RF pulse, followed by application of a magnetic field gradient, leading to formation of an MRI signal called a gradient recalled echo. The pulse sequence is then repeated until enough gradient recalled echoes have been acquired to create MR images. The TR and TE are short, leading to rapid acquisition times. As such, this pulse sequence is commonly used to obtain precontrast and postcontrast T1-weighted images.

In addition, in-phase T1-weighted GRE images (where signals from fat and water protons in the same voxel add to each other) are used to detect iron deposition, metal, and gas in tissues as manifested by a loss of signal intensity relative to out-of-phase T1-weighted images, whereas out-of-phase T1-weighted GRE images (where signals from fat and water protons in the same voxel cancel each other) are used to detect presence of microscopic lipid within tissues as manifested by a loss of signal intensity relative to in-phase T1-weighted images.

30. What is signal intensity (SI)?

SI is the descriptor of how bright or dark a tissue is on an MR image. As SI is not calibrated to a standard, it is important to describe SI of a tissue of interest in comparison to another reference tissue such as skeletal muscle or liver.

31. What are T1-weighted images?

T1-weighted images are MR images that display SIs of tissues based on their T1 properties and are typically acquired using short TR and TE values.

32. What are T2-weighted images?

T2-weighted images are MR images that display SIs of tissues based on their T2 properties and are typically acquired using long TR and TE values.

33. What typically has high SI on T1-weighted images?

Fat, proteinaceous fluid, subacute hemorrhage, paramagnetic substances such as melanin, and gadolinium-based contrast material have high T1-weighted SI relative to skeletal muscle. Note that fat may alternatively have low SI on T1-weighted images if fat suppression is applied.

34. What typically has high SI on T2-weighted images?

Fat (on T2-weighted FSE images), simple fluid, fluid-filled organs, cysts, and hemangiomas have high T2-weighted SI relative to skeletal muscle. In general, if fluid (such as in the cerebrospinal fluid, gallbladder, or bladder) is seen to have very high SI on an MR image, then it is likely T2-weighted, whereas if it has low SI, then it is likely T1-weighted.

35. What typically has low SI on both T1-weighted and T2-weighted images?

Gas, cortical bone, fibrous tissue (such as in ligaments and tendons), chronic hemorrhage, iron, metal, and fast flow in blood vessels have low T1-weighted and T2-weighted SI relative to skeletal muscle.

36. Why is it important to acquire precontrast and postcontrast images with the same imaging parameters?

Tissue SIs will change from precontrast to postcontrast images if the imaging parameters are changed but will also change if tissue enhancement following intravenous contrast administration is present. Thus, if the imaging parameters differ between precontrast and postcontrast image acquisitions, it would not be possible to determine whether an observed increase in tissue SI on postcontrast images is due to true enhancement or is artifactual in nature.

37. What is diffusion-weighted imaging (DWI)?

DWI is a functional MR imaging technique that provides information about tissue structure, water content, and cellularity by measurement of the average diffusivity of water molecules due to Brownian motion within a tissue of interest. DWI is useful to detect acute cerebral infarction and also to detect and characterize malignant lesions in the body.

38. What is diffusion-tensor imaging (DTI)?

DTI is a functional MR imaging technique that provides information about tissue microstructure through measurement of the direction-specific diffusivities of water molecules within a tissue of interest. DTI is particularly useful to assess the white matter tracts of the brain for pretreatment planning in patients with brain tumors.

39. What is magnetic resonance spectroscopy (MRS)?

MRS is a functional technique that provides quantitative information about the endogenous molecular composition of a tissue of interest. The data are typically displayed as a spectrum of chemical compound abundances, most often based on the magnetic properties of the hydrogen atom nuclei. MRS is most commonly used clinically to characterize brain lesions.

KEY POINTS

- US is a structural imaging technique that uses high-frequency mechanical ultrasound waves to create real-time tomographic images.
- CT is a structural imaging technique that uses x-rays to create tomographic images.
- MRI is a structural and functional imaging technique that uses magnetism and RF waves to create tomographic images.
- Echogenicity, attenuation, and signal intensity are the descriptors of how bright or dark tissues are on US, CT, and MR images, respectively.
- If fluid has very high SI on an MR image, then it is likely T2-weighted, whereas if it has low SI, then it is likely T1-weighted.

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CHAPTER 3

INTRODUCTION TO NUCLEAR MEDICINE AND MOLECULAR IMAGING

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1. **What is molecular imaging?**
   Molecular imaging is the visualization, characterization, and measurement of biologic processes at the molecular and cellular levels in humans and other living systems. It is essentially a noninvasive means to study in vivo biochemistry and cell biology and is useful to optimize diagnosis and therapy of disease in individualized patients. Nuclear medicine techniques and optical imaging techniques are most commonly used to perform molecular imaging, the former predominantly in humans and the latter predominantly in small animals for preclinical research.

2. **What is nuclear medicine, and how is a nuclear medicine test performed?**
   A radioactive compound (i.e., a radiotracer) that targets a molecular process, cellular process, or disease of interest is administered to a patient. Photons are emitted from the radiotracer in the patient, and an imaging detector is used to detect the distribution of the radiotracer. Images are then created by a computer system. The main nuclear medicine imaging techniques include planar scintigraphy, single photon emission computed tomography (SPECT), and positron emission tomography (PET). Nuclear medicine techniques are used not only for diagnostic purposes, but also less commonly to treat cancer, in which case the radiotracers used accumulate in tumor sites and also emit charged particles that promote cancer cell death.

3. **How does molecular imaging differ from structural imaging?**
   Molecular imaging allows for the noninvasive functional and molecular characterization of normal tissues and disease processes of interest, even when morphologic changes in tissues have not yet occurred. Structural imaging (such as with radiography, computed tomography [CT], magnetic resonance imaging [MRI], and ultrasonography [US]) allows for the noninvasive anatomic assessment of normal tissues and disease conditions based on morphologic and gross functional alterations that occur. Molecular imaging techniques typically have higher contrast resolution (i.e., the ability to distinguish between differences in image intensity) and lower spatial resolution (i.e., the ability to distinguish two adjacent structures as being separate) compared to structural imaging techniques. As such, molecular imaging and structural imaging techniques are complementary.

4. **What is the difference between x-rays used in radiography and CT and gamma rays used in nuclear medicine techniques?**
   X-rays and gamma rays are both types of ionizing electromagnetic radiation (i.e., they are photons that are energetic enough to remove electrons from other atoms or molecules) with wavelengths shorter than those of visible light. X-rays are emitted by electrons located outside of the nucleus of an atom, whereas gamma rays are emitted by unstable nuclei within atoms and have higher energies than x-rays. Diagnostic x-ray imaging is referred to as transmission imaging, since images are formed by the transmission of x-ray photons from an external source (outside the patient) through the patient to external detectors. Nuclear medicine imaging is referred to as emission imaging because images are formed by the emission of gamma ray photons from an internal source (inside the patient) through the patient to external detectors.

5. **What is radioactivity, and when was it discovered?**
   Radioactivity (i.e., radioactive decay) is the process by which unstable atoms that do not have sufficient binding energy to hold their nuclei together emit ionizing radiation, and it occurs in exponential fashion. Alpha decay occurs when an alpha particle (identical to a helium nucleus) is emitted. Beta decay occurs when a beta particle (such as a positron) is emitted. Gamma decay occurs when a gamma ray is emitted during transition of an atomic nucleus to a lower energy state. Henri Becquerel discovered spontaneous radioactivity from uranium in 1896, and Pierre and Marie Curie discovered radium and polonium in 1898. As a result, all three received the Nobel Prize in Physics in 1903.

6. **When was the positron discovered?**
   Carl Anderson discovered the positron (the "positive electron") in 1932 and subsequently received the Nobel Prize in Physics in 1936. Positron emission by certain radioisotopes makes PET imaging feasible.

7. **How are radioisotopes and radiotracers created?**
   Generators are devices that contain a radioactive parent radioisotope with a relatively long half-life that decays to a short-lived daughter radioisotope, which is then used for diagnostic imaging or therapy. The most commonly used one is the technetium-99m (^{99m}Tc) generator, which has molybdenum-99 (^{99}Mo) as the parent radioisotope. As decay of

Table 3-1. Commonly Used Radioisotopes in Diagnostic Nuclear Medicine

NAME	PHYSICAL HALF-LIFE	USED WITH
Technetium-99m (^{99m}Tc)	6 hours	Planar scintigraphy, SPECT
Iodine-123 (^{123}I)	13.2 hours	Planar scintigraphy, SPECT
Indium-111 (^{111}In)	67 hours	Planar scintigraphy, SPECT
Thalium-201 (^{201}Tl)	73.1 hours	Planar scintigraphy, SPECT
Gallium-67 (^{67}Ga)	78.3 hours	Planar scintigraphy, SPECT
Xenon-133 (^{133}Xe)	5.3 days	Planar scintigraphy, SPECT
Rubidium-82 (^{82}Rb)	1.3 minutes	PET
Oxygen-15 (^{15}O)	2 minutes	PET
Nitrogen-13 (^{13}N)	10 minutes	PET
Carbon-11 (^{11}C)	20 minutes	PET
Gallium-68 (^{68}Ga)	68 minutes	PET
Fluorine-18 (^{18}F)	110 minutes	PET
Copper-64 (^{64}Cu)	12.7 hours	PET
Iodine-124 (^{124}I)	4.2 days	PET

^{99}Mo occurs, ^{99m}Tc is formed and can then be eluted for use with various molecules to obtain scans of different physiologic processes. Cyclotrons are circular devices in which charged particles are accelerated and deflected into a target to create radioisotopes such as carbon-11 (^{11}C) and fluorine-18 (^{18}F). Medical grade nuclear reactors are sometimes used to create other isotopes.

8. What are some commonly used radioisotopes in diagnostic nuclear medicine?

See Table 3-1. Such radioisotopes are often used to label specific molecular compounds that target a molecular process, cellular process, or disease of interest which may then be imaged.

9. What is the physical half-life of a radioisotope?

The physical half-life of a radioisotope is the average amount of time it takes for half of the original radioactive compound to have undergone radioactive decay. After 5 half-lives, approximately 97% of the original radioactivity of the compound will have decayed. Note that it is not possible to predict when exactly an individual radioisotope atom in the compound will decay.

10. What units are used to measure radioactivity?

To measure the dose of radioactivity, the becquerel (Bq) is equal to 1 disintegration per second (dps) and is the SI unit of radioactivity. The curie (Ci) is equal to 3.7×10^{10} dps, or 37 MBq, which is approximately equal to the radioactivity of 1 gram of radium-226 (^{226}Ra), and is the non-SI unit of radioactivity. The effect of ionizing radiation on the body is typically measured by the Sievert (Sv), the SI unit, or the rem (roentgen equivalent in man), the non-SI unit, where 1 Sv = 100 rem. One Sv is defined as the biologic effect of depositing one joule of radiation energy in one kilogram of human tissue.

11. What is a dose calibrator?

A dose calibrator is a device that is used in nuclear medicine to measure the amount of radioactivity in a radiotracer before it is administered to a patient.

12. How are nuclear medicine imaging tests generally performed?

A radiotracer is administered to a patient (most commonly intravenously, although oral or inhalational routes are also possible). After waiting for a certain delay time to allow for biodistribution of the radiotracer, the patient is then placed into the scanner. For planar scintigraphy and SPECT, gamma rays are emitted by the radioactive isotopes in the radiotracers. For PET, positrons that are emitted by the radioactive isotopes in the radiotracer molecules travel several millimeters within tissue before annihilating with electrons that are encountered, leading to emission of two gamma rays in opposite directions. The gamma rays leave the body, pass through a collimator (in planar scintigraphy and SPECT), and are detected by one or more scintillation crystals in detectors surrounding the patient. The light signals created by the scintillation crystals are then detected by photomultiplier tubes (PMT), which lead to creation of voltage signals that are digitized for computers to process. Ultimately, when enough signals are detected, the computer reconstructs images that reflect the spatial distribution and amount of accumulation of the radiotracer in organs/

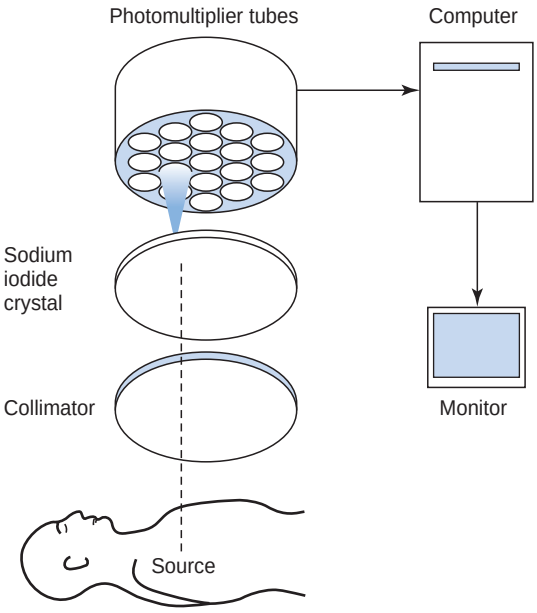

Figure 3-1. Schematic for apparatus of gamma camera system.

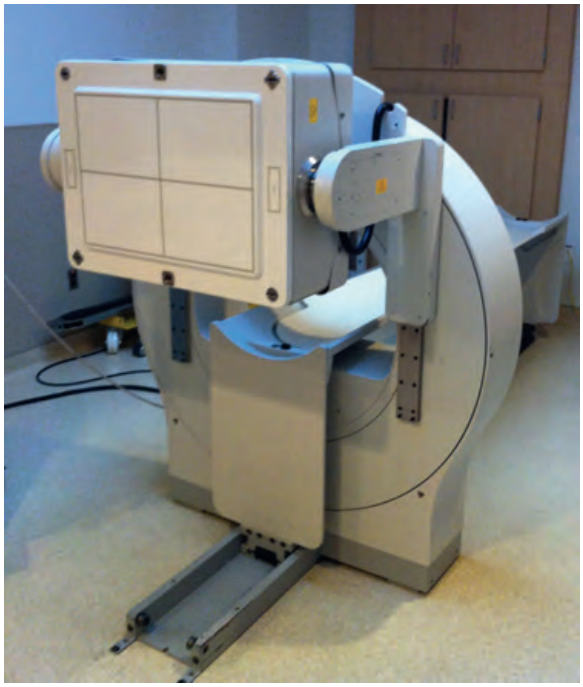

Figure 3-2. Typical single head gamma camera system used in planar scintigraphy.

tissues of the body (which depend on the properties of the administered radiotracer and the disease states present in the patient).

13. What is planar scintigraphy?

Planar scintigraphy is a nuclear medicine technique in which non-tomographic (2D) planar images of the spatial distribution and amount of accumulation of a radiotracer in the body are created. This is performed using a gamma camera system (Figures 3-1 and 3-2), including a collimator made of perforated or folded lead to absorb most emitted radiation from the radiotracer except that arriving perpendicular to the detector face, and a thallium-doped sodium iodine scintillation crystal. Unfortunately, the collimator wastes > 99% of the emitted signal and is rate-limiting. Planar images can be obtained either statically or dynamically over time to create a video of a particular physiological process of interest.

14. What are some examples of common clinical applications of planar scintigraphy?

- A ventilation-perfusion (V/Q) scan is useful to assess for acute pulmonary embolism.
- A three-phase bone scan is useful to determine if osteomyelitis is present.
- A thyroid scan is useful to determine if a thyroid nodule is benign or malignant.
- A hepatobiliary scan is useful to assess for acute cholecystitis, bile duct obstruction, or biliary leak.
- A bleeding scan is useful to localize sites of lower gastrointestinal hemorrhage.

15. What is SPECT?

SPECT is a nuclear medicine technique in which tomographic (cross-sectional) images of the spatial distribution and amount of accumulation of a single gamma ray emitting radiotracer in the body are created. It also requires the use of a collimator, which generally results in lower sensitivity and poorer image quality compared to PET. Furthermore, SPECT requires the use of radioisotopes that emit single gamma rays, which are usually metallic elements that are difficult to incorporate into biologically important compounds. SPECT/CT scanners (Figure 3-3) are most often employed for SPECT imaging to provide coregistered molecular and structural images.

16. What are some examples of common clinical applications of SPECT/CT?

- ^{111}In-octreotide SPECT/CT is useful to assess neuroendocrine tumors before and after treatment.
- ^{99m}Tc-sestamibi SPECT/CT is useful to preoperatively localize parathyroid adenomas, particularly when ectopic in location.
- ^{201}Tl SPECT/CT is useful to detect and evaluate the effects of coronary artery disease on myocardial perfusion.

17. What is PET?

PET is a nuclear medicine technique in which tomographic (cross-sectional) images of the spatial distribution and amount of accumulation of a positron emitting radiotracer in the body are created. Collimators are not required in PET

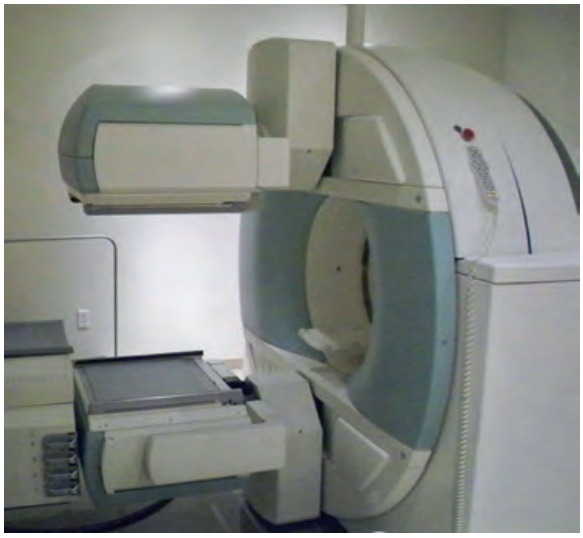

Figure 3-3. Typical dual head gamma camera SPECT/CT scanner.

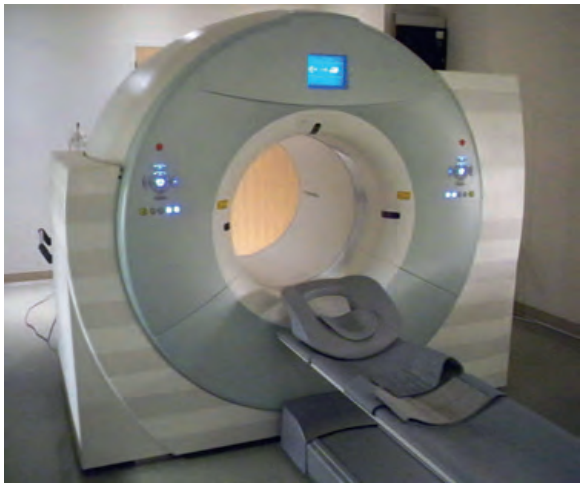

Figure 3-4. Typical PET/CT scanner with gantry (which contains x-ray tube for CT and scintillation crystals for PET) and patient table.

because pairs of colinear gamma ray photons emitted in opposite directions from areas of positron annihilation are used to localize sites of radiotracer uptake in the body. This is performed by a process known as coincidence detection, where only photons with the correct energy that are detected simultaneously by detectors located 180 degrees from each other are registered as true events and used to create images. Today, PET/CT scanners (Figure 3-4) are most commonly used for PET imaging to provide coregistered molecular and structural images, improving image quality, anatomic localization of sites of radiotracer uptake, and diagnostic performance. PET/MRI scanners have recently become available for clinical use, providing the additional advantages of decreased radiation dose and improved soft tissue contrast resolution afforded by MRI, but they are much more expensive, require additional safety measures and personnel training for implementation, and require longer image acquisition times compared to those for PET/CT.

18. What are some examples of common clinical applications of PET/CT?

- ^{18}F-fluorodeoxyglucose (FDG) PET/CT is useful to stage cancers at baseline, to guide treatment, and to assess tumor response following therapeutic intervention.
- FDG PET/CT is also useful to localize seizure foci in the brain, to assess patients with cognitive impairment, and to evaluate for brain tumor recurrence.
- ^{82}Rb PET/CT is useful to detect and evaluate the effects of coronary artery disease on myocardial perfusion.

- ^{18}F-sodium fluoride (NaF) PET/CT is useful to detect and evaluate osteoblastic metastatic disease in patients with cancer.
- ^{11}C-acetate PET/CT is useful to detect the presence and location of recurrent prostate cancer in men with biochemical recurrence following treatment.

19. What is a standardized uptake value (SUV)?

An SUV is a quantitative measure of PET radiotracer uptake in a tissue of interest and is a unitless value. It is calculated as the ratio of tissue radiotracer activity concentration (i.e., accumulated radiotracer dose in a tissue of interest/volume of the tissue of interest) compared to whole body radiotracer activity concentration (i.e., injected radiotracer dose/body weight [where one assumes that 1 g of body weight = 1 ml volume]). If the distribution of an injected radiotracer were uniform throughout the body, then the SUV would be measured as 1 everywhere. Maximum SUV (SUVmax) is the SUV of the hottest voxel within a lesion. Mean SUV (SUVmean) is the average of the SUVs of all voxels within a lesion. Peak SUV (SUVpeak) is the average of the SUVs of a subset of voxels centered about the hottest voxel within a lesion.

20. What is total lesional glycolysis (TLG)?

TLG (also called metabolic volumetric product [MVP]) is a global measure of disease burden in the body and is derived by first calculating the product of SUV and volume for each lesion and then summing these products over all lesions encountered in the body. TLG measurements are generally useful to prognosticate patient outcome and to quantitatively assess treatment response.

21. What is optical imaging, and how does it work?

Optical imaging utilizes nonionizing electromagnetic radiation near or within the visible light spectrum to create images and is often used in conjunction with a variety of fluorescent or bioluminescent compounds that target a molecular process, cellular process, or disease of interest. It has a very high sensitivity of detection, but it suffers from a limited depth of penetration of light into tissues and also from light scattering. As a result, optical imaging is predominantly used in preclinical small animal research to study the biodistribution, pharmacokinetics, or pharmacodynamics of new therapeutics that are being developed.

22. What is the difference between fluorescence and bioluminescence?

Fluorescence occurs when a molecule absorbs light from an outside source and then emits light due to the excitation and relaxation of electrons within the molecule, respectively. An example of a fluorescent compound is green fluorescent protein (GFP). Bioluminescence describes light creation by living organisms via chemical reactions between molecules without requiring the absorption of light from an outside source. For example, enzymes called luciferases act on pigment molecules called luciferins to create bioluminescence in insects such as fireflies, marine organisms, and some fungi and bacteria. Fluorescent and bioluminescent molecular compounds are commonly used in conjunction with optical imaging in preclinical research studies.

23. What is Cherenkov radiation?

Cherenkov radiation was discovered and characterized by Pavel Cherenkov in 1934 (for which he received a Nobel Prize in Physics in 1958 along with Ilya Frank and Igor Tamm) and is observed as a faint blue glow such as may be seen in the water surrounding nuclear reactors. It is the equivalent of the sonic boom for light, and it occurs when a charged particle moves through a medium at a speed greater than the speed of light in that medium (which is less than the speed of light in a vacuum), leading to emission of visible light photons. Optical imaging techniques based on detection of Cherenkov radiation along with Cherenkov specific contrast agents are currently being utilized in preclinical research studies.

KEY POINTS

- Molecular imaging is complementary with structural imaging.
- Nuclear medicine techniques are predominantly used in the clinical setting for molecular imaging, whereas optical imaging techniques are predominantly used in preclinical research.
- Planar scintigraphy, SPECT, and PET imaging are the primary nuclear medicine molecular imaging techniques available. They are used to image the spatial distribution and amount of accumulation of an administered radiotracer in organs/tissues of the body (which depend on the properties of the radiotracer and the disease states present).
- SUV is a quantitative measure of PET radiotracer uptake in a tissue of interest.

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CHAPTER 4

INTRODUCTION TO IMAGE PROCESSING, VISUALIZATION, AND ANALYSIS

Drew A. Torigian, MD, MA, FSAR, and Jayaram K. Udupa, PhD

1. **What is a digital image?**
   A digital image is an image discretized in spatial coordinates and in brightness. It can be represented by a multidimensional array of integers.
2. **What is the difference between a pixel and a voxel?**
   A pixel, or picture element, is the smallest element of a 2D digital image that can be individually processed, whereas a voxel, or volume element, is the smallest element of a 3D digital image that can be individually processed. A voxel that is the same length in all three dimensions is called an isotropic voxel.
3. **What is image reconstruction?**
   Image reconstruction is a mathematical technique implemented in computers within scanners to reconstruct tomographic or volumetric images from acquired projectional data of a patient. For example, filtered back projection (FBP) and iterative reconstruction (IR) methods are commonly used to create tomographic images in CT.
4. **What is the field of view (FOV) of an image?**
   FOV is the width of an image, which tends to represent the width of the body region that is imaged by the scanner.
5. **What is the matrix size of an image?**
   Matrix size is the number of pixels along the length and width of a digital image. This can be the same in both directions (e.g., 512×512 in CT) or can differ between the two directions (e.g., 256×192 in MRI).
6. **What is signal-to-noise ratio (SNR)?**
   SNR is the ratio of the mean intensity (i.e., signal) of an object on an image to the standard deviation of the background noise on an image and is a rough measure of image quality.
7. **What is contrast-to-noise ratio (CNR)?**
   CNR is the difference in SNR between two objects or tissue regions on an image that are adjacent to one another and is another commonly used measure of image quality to indicate the measureable contrast between the two regions.
8. **What is spatial resolution?**
   Spatial resolution is the ability to portray two separate but adjacent objects as distinct on an image. It is a function of pixel (or voxel) size, is calculated as FOV/matrix size, and is typically measured in line pairs per millimeter (lp/mm), referring to the ability of an imaging technique to distinguish two closely placed line objects as separate.
9. **What is contrast resolution?**
   Contrast resolution is the ability to portray tissues with different intensities in different shades of gray on an image.
10. **What is temporal resolution?**
    Temporal resolution is the ability to acquire multiple images in a short amount of time. This factor becomes important when imaging moving objects such as the heart, lungs, and joints.
11. **What is a modulation transfer function (MTF)?**
    An MTF is a measure of the resolution capability of an imaging system. It is calculated as the ratio of output contrast to input contrast in an imaging system. It indicates the imaging system's ability to retain sharpness or its blurring characteristics.
12. **What is quantitative radiology (QR)?**
    QR is the quantitative assessment of medical images to evaluate normal states and the severity, degree of change, or status of abnormal disease states relative to normal. This involves the development, standardization, and optimization of image acquisition protocols, computer-aided visualization and analysis (CAVA) methods, and reporting structures. QR is increasingly becoming an integral part of clinical radiology practice.
13. **What is the purpose of computer-aided visualization and analysis (CAVA)?**
    The purpose of CAVA is to produce quantitative and improved qualitative information about one or more objects of interest within digital images through the use of a computer. The four major operations used in CAVA are preprocessing, visualization, manipulation, and analysis.

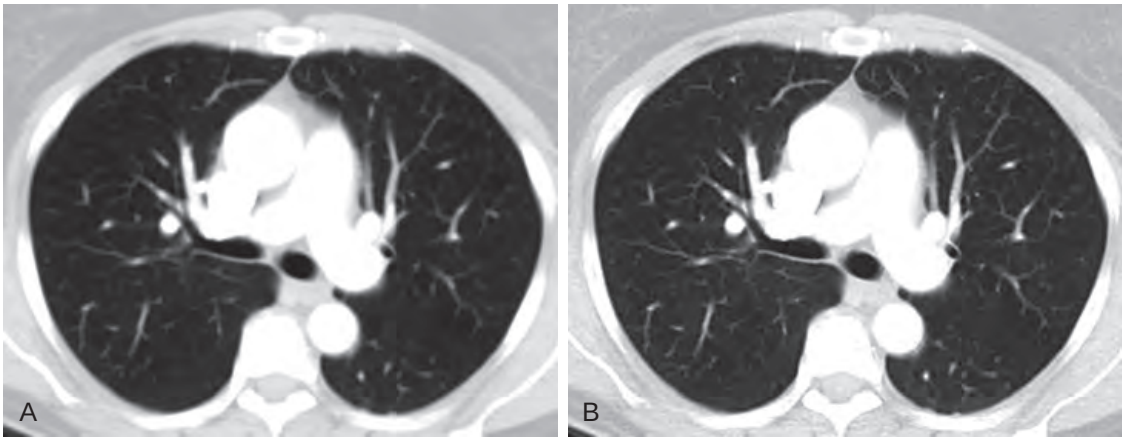

Figure 4-1. Filtering. **A,** Chest CT image reconstructed with a suppressing filter. Note smoother appearance of lungs. **B,** Same chest CT image reconstructed with an enhancing filter. Note sharper appearance of lungs.

14. What is image preprocessing?

Image preprocessing is a set of computer-based techniques used to prepare an image dataset to facilitate subsequent visualization, manipulation, and analysis. Some commonly used preprocessing techniques include volume of interest (VOI) restriction, filtering, interpolation, registration, segmentation, and image algebraic operations (e.g., addition, subtraction, etc.).

15. What is VOI restriction?

This is a preprocessing technique used to reduce the amount of unneeded data in an image dataset. For example, one may delete some image slices at the upper and lower portions of a stack of contiguous axial tomographic images, crop slices to reduce the length and width of each slice, or remove certain unwanted objects such as the scanner table from the image slices.

16. What is filtering?

Filtering is a preprocessing technique used to enhance wanted (object) information and suppress unwanted (noise, artifact, or background) information in an image dataset. The most commonly used enhancing filter is an edge enhancing operation, leading to sharper image quality, whereas the most commonly used suppressing filter is a smoothing operation, leading to smoother image quality (Figure 4-1).

17. What is interpolation?

Interpolation is a preprocessing technique used to change the level of discretization (pixel or voxel size) in an image. For example, one may reslice a volumetric image dataset into a set of tomographic slices of a prespecified thickness and orientation.

18. What is registration?

Registration is a preprocessing technique used to match two image datasets or objects within images as closely as possible. This can be performed with a rigid transformation (using translation and rotation operations) or with a non-rigid transformation (also using deformation operations). For example, one may register PET and CT image datasets acquired from a patient to create hybrid PET/CT images. As another example, one may register MRI scans acquired from a patient on two separate occasions to aid in detection of disease change over time.

19. What is segmentation?

Segmentation is a preprocessing technique used to recognize and delineate objects in an image dataset. Recognition is the determination of an object's approximate whereabouts in an image, which is a high-level task in which humans typically outperform computers. Delineation is the determination of an object's precise spatial extent and composition in an image, which is a low-level task in which computers typically outperform humans. For example, one may segment the lungs from the thorax on a chest CT study and then segment areas of lung emphysema (Figure 4-2).

20. What is thresholding?

Thresholding is a commonly used and the simplest segmentation technique in which a gray scale threshold value range or interval is applied to an image dataset. All pixels (or voxels) with gray scale values lying in the threshold range are included in the segmented region, whereas the others are not.

21. What is the purpose of image visualization?

Image visualization is used to create visual renditions of objects of interest in an image dataset to enhance one's understanding about such objects.

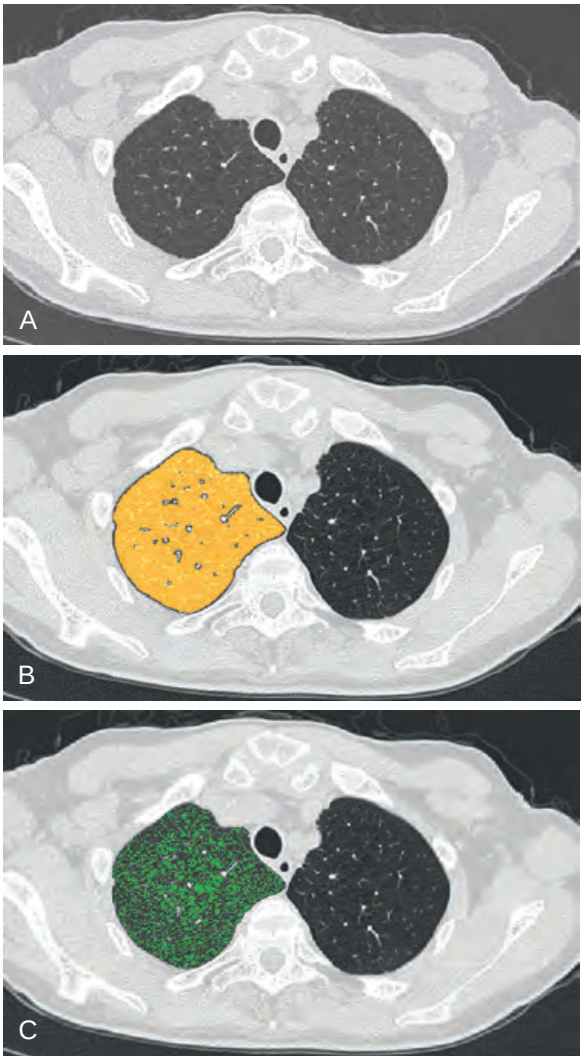

Figure 4-2. Segmentation. **A,** Chest CT image in patient with mild emphysema. **B,** Same chest CT image with segmented right lung (orange color overlay). **C,** Same chest CT image with segmented emphysema in right lung (green color overlay).

22. What are some ways to visualize tomographic images?

In section mode, images can be visualized as axial, sagittal, coronal, or oblique sections, or even as curved sections (also known as multiplanar reformations [MPRs]). Curved MPRs are commonly used to analyze vascular structures on CT or MR angiography.

In volume mode, images can be visualized with the following renderings (Figure 4-3):

- Maximum intensity projection (MIP): A 2D rendered image is displayed in which the gray scale intensity assigned to each pixel is the maximum of the intensities of all voxels encountered along the projection axis. This is most commonly used when objects of interest are the brightest in the image (e.g., enhancing vessels and osseous or calcified structures).
- Minimum intensity projection (MinIP): A 2D rendered image is displayed in which the gray scale intensity assigned to each pixel is the minimum of the intensities of all voxels encountered along the projection axis. This is most commonly used when objects of interest are the darkest in the image (e.g., lungs, air-filled tracheobronchial tree, and air-filled bowel).
- Surface-shaded display (SSD): A 2D rendered image of an object surface is displayed. This is infrequently used given the availability of volume rendering techniques.
- Volume-rendered (VR): A 2D rendered image of an object volume is displayed in which each voxel is assigned a brightness level or color and an opacity value ranging from 0% to 100%, which can be adjusted interactively as desired. The viewpoint is often external to the object of interest, although it can also be located internal to the

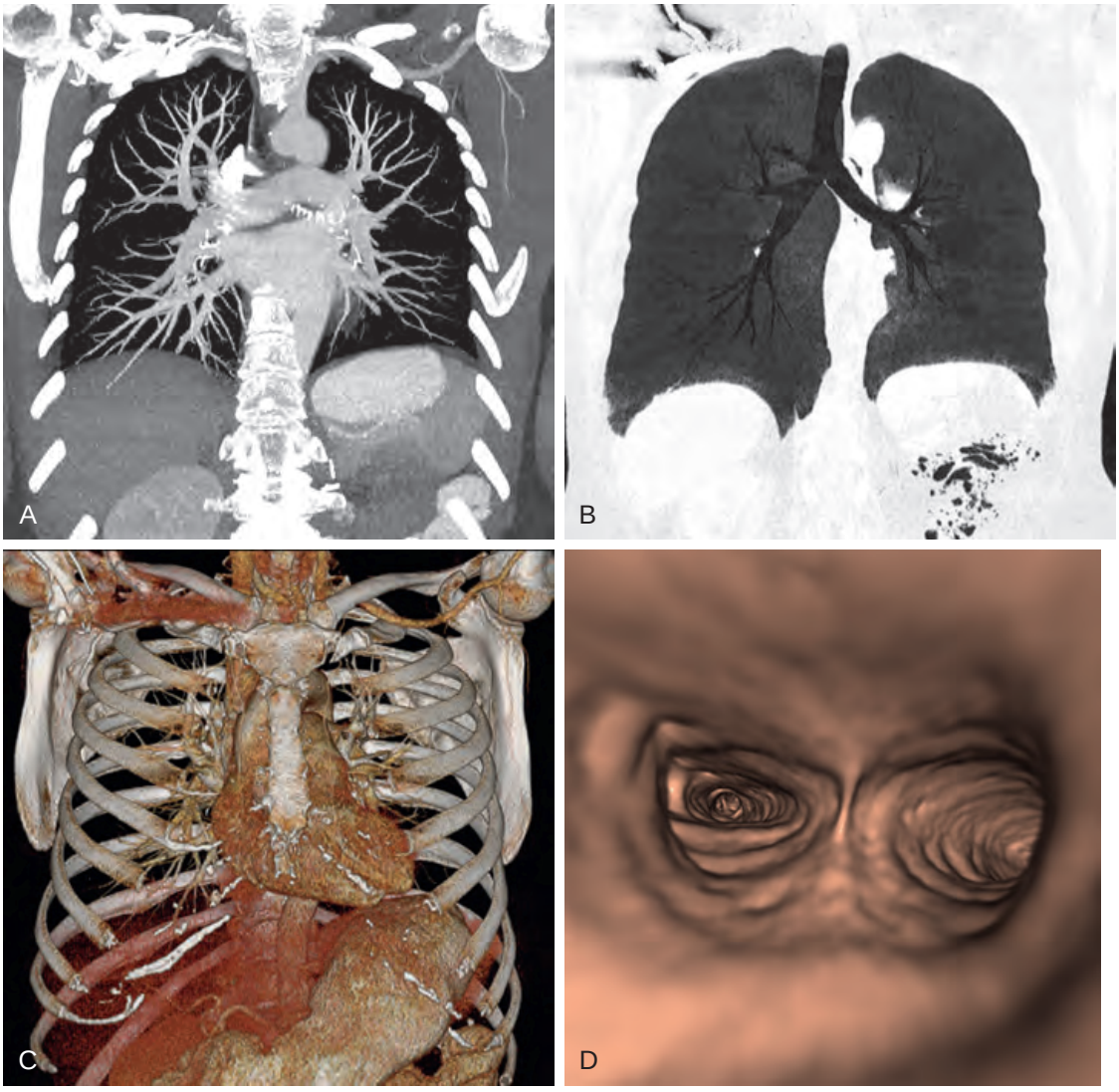

Figure 4-3. Volume mode image renderings. **A,** Chest CT maximum intensity projection (MIP) image. Note good visualization of high attenuation contrast-enhanced pulmonary vascular structures. **B,** Chest CT minimum intensity projection (MinIP) image. Note good visualization of very low attenuation structures such as gas-filled lungs, tracheobronchial tree, and upper abdominal bowel loops. **C,** Chest CT volume-rendered (VR) image from external viewpoint. Note good visualization of 3D spatial relationships of thoracic skeleton, heart, and upper abdominal organs. **D,** Virtual endoscopic chest CT VR image within trachea. Note normal appearing tracheal bifurcation and proximal mainstem bronchi.

object of interest to create virtual endoscopic (also called endoluminal or "fly through") images. Virtual endoscopy is commonly used in virtual CT colonoscopy to visualize the large bowel and also in virtual CT bronchoscopy to visualize the tracheobronchial tree.

23. What is the difference between window level and window width?

Window level is the gray scale value that is selected to be displayed as the midlevel intensity on an image and determines the displayed image brightness. Window width is the range of gray scale values that is selected to be displayed in image voxels as shades of gray around the selected window level and determines the displayed image contrast. For gray scale values above or below this selected range, image voxels are displayed white and black, respectively. A narrow window width provides high contrast. Preset window level and width combinations are commonly used to optimally display certain tissue types on digital images.

24. What is the purpose of image manipulation?

Image manipulation is used to interactively change visual renditions of objects of interest in an image dataset to enhance one's understanding about such objects. For example, one may simulate performance of a surgical procedure

on a patient using an image dataset acquired from the patient or may use image datasets from multiple patients to develop new interventional techniques to treat various disease conditions.

25. What is the purpose of image analysis?

Image analysis is used to extract quantitative information about one or more objects of interest from image datasets. For example, one may quantify the morphological features of objects, such as size, curvature, area, volume, shape, position, boundary characteristics, and interobject spatial relationships, or the change in these parameters with motion, in the case of dynamic objects. Alternatively, one may quantify the intensity features of objects, such as histogram-based intensity properties (mean, maximum, minimum, skewness, kurtosis) or texture-based intensity properties (contrast, homogeneity, energy, entropy), or the change in these parameters with motion, in the case of dynamic objects.

26. What is the purpose of computer-aided diagnosis (CAD)?

CAD is used for automatic detection and characterization (i.e., diagnosis) of lesions of interest on image datasets. Typically, CAD is used to improve the diagnostic accuracy and efficiency of image interpretation by a radiologist or nuclear medicine physician. For example, CAD can be used to aid in the detection and characterization of lung nodules on chest CT, of colon polyps and masses on virtual CT colonoscopy, and of breast cancers on mammography.

27. What is a biomarker?

A biomarker (biologic marker) is a characteristic that is objectively measured and evaluated as an indicator of normal biologic processes, pathogenic processes, or pharmacologic responses to a therapeutic intervention. Imaging biomarkers are obtained from image analysis.

28. What is a clinical endpoint?

A clinical endpoint is a characteristic that reflects how a patient feels, functions, or survives and is typically considered as the primary endpoint in clinical research studies. For example, survival and improvement in quality of life are clinical endpoints.

29. What is a surrogate endpoint?

A surrogate endpoint is a biomarker that may be used in place of a clinical endpoint so that a clinical research study can be practically conducted or completed more quickly. For example, disease response seen on imaging or on laboratory testing following therapy is a surrogate endpoint. Please note that not all biomarkers are surrogate endpoints.

30. What is radiomics?

Radiomics is a field of study in QR that involves the high-throughput extraction of large numbers of quantitative features from diagnostic images. The purpose is to develop new quantitative imaging biomarkers that may be clinically useful to improve the diagnostic accuracy of disease detection, staging, or phenotyping (e.g., characterization of specific disease histopathology, prediction of disease response to therapy, prognostication of patient outcome).

31. What is radiogenomics?

Radiogenomics is a field of study in QR and the basic sciences that is focused on defining associations between image-based phenotypes and molecular phenotypes of disease. This may be useful to better understand the biologic significance of certain image-based features encountered on diagnostic imaging or to develop and validate new imaging biomarkers to address unanswered clinical questions.

KEY POINTS

- Quantitative radiology (QR) is the quantitative assessment of medical images to evaluate normal states and the severity, degree of change, or status of abnormal disease states relative to normal. This involves the development, standardization, and optimization of image acquisition protocols, computer-aided visualization and analysis (CAVA) methods, and reporting structures.
- CAVA provides quantitative information about objects of interest within digital images and involves the use of image preprocessing, visualization, manipulation, and analysis.
- A biomarker (biologic marker) is a characteristic that is objectively measured and evaluated as an indicator of normal biologic processes, pathogenic processes, or pharmacologic responses to a therapeutic intervention. Imaging biomarkers are obtained from image analysis.
- Spatial resolution is the ability to display two separate but adjacent objects as distinct on an image.
- Contrast resolution is the ability to display tissues with different intensities as having distinct shades of gray on an image.

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CHAPTER 5

COMPUTERS IN RADIOLOGY

Mindy Y. Licurse, MD, and William W. Boonn, MD

1. What is PACS?

PACS stands for Picture Archiving and Communication System. On the most basic level, PACS integrates image acquisition modalities, workstation displays, the image archiving system, and the underlying network.

2. How are PACS images stored?

The PACS archive traditionally has been composed of short-term and long-term storage. Short-term storage is usually composed of redundant arrays of inexpensive (or independent) discs (RAID) arrays that provide quick access to image data. After a certain amount of time (3 to 30 days, depending on the size of the short-term archive), images from the short-term archive are moved to the long-term archive, which is usually composed of magnetic tape or magneto-optical media. Images cannot be viewed directly from the long-term archive. Instead, images need to be "fetched" from the long-term archive and copied back to the short-term archive before being viewed on a workstation. This compromise was made because of the high cost of RAID storage. The cost of RAID storage has decreased enough more recently so that several PACS archives are now being designed as "always online" systems. These new systems are composed only of RAID arrays, which essentially place all images in the short-term archive and eliminate the need for fetching.

3. What is image compression?

Image compression is the process of reducing image file size using various mathematical algorithms. Compression is usually expressed as a ratio (e.g., 10:1). A 10-megabyte (MB) file that is compressed at a ratio of 10:1 would have a final size of 1 MB. Generally, as compression ratios increase, file sizes decrease. However, a price is inevitably paid in decreased image fidelity.

4. What is the difference between "lossy" and "lossless" compression?

Encoding an image is a process that converts a raw image (e.g., the original radiograph) into a more compact coded file. Decoding converts the coded file to a decoded image. If the raw image and the decoded image are the same, the compression method is considered lossless. If there is a difference between the raw image and the decoded image, the method of encoding and decoding is considered lossy. Lossless compression can usually achieve ratios of 2:1 or 3:1. Lossy compression can achieve much higher compression ratios; however, overcompression may destroy fine detail, making the image unacceptable for diagnostic purposes.

5. What is RIS?

RIS stands for Radiology Information System. RIS is the core system responsible for managing workflow within a radiology department. Tasks include patient scheduling and tracking, examination performance tracking, examination interpretation, billing, and handling of radiology reports including result distribution. RIS must work optimally with the PACS to properly enable information sharing. Over the past several years, with the evolution of radiology to filmless environments, RIS capabilities have increased tremendously in addition to merging of RIS/PACS interdependent functionality.

6. What is HIS?

HIS stands for Hospital Information System. HIS manages patient demographics; insurance and billing; and often other clinical information systems, including laboratory results, physician orders, and electronic medical records.

7. What is DICOM?

DICOM stands for Digital Imaging and Communications in Medicine. It is a standard that establishes rules that allow medical images and associated information to be exchanged between imaging equipment from different vendors, computers, and hospitals. A computed tomography (CT) scanner produced by vendor A and a magnetic resonance imaging (MRI) scanner produced by vendor B can send images to a PACS from vendor C using DICOM as a common language. In addition to storing image information, other DICOM standard services include query/retrieve, print management, scheduling of acquisition and notification of completion, and security profiles.

8. What determines image storage size?

Image size, generally expressed in megabytes, is determined by spatial resolution and bit depth. Spatial resolution for a two-dimensional (2D) image is defined by a matrix of horizontal and vertical pixels. A single image in a typical CT

scan is composed of a matrix of 512 vertical pixels × 512 horizontal pixels, whereas a chest radiograph image might have a matrix size of 2500 vertical pixels × 2000 horizontal pixels. For a given anatomic area of interest, images with a larger matrix size have greater spatial resolution.

Bit depth is defined by the number of shades of gray within the image, where 2^n equals shades of gray and n equals bit depth. An image with a bit depth of 1 has 2 shades of gray (pure black and pure white). A 6-bit image contains 64 shades of gray; 7-bit, 128 shades; 8-bit, 256 shades; and 12-bit, 4096 shades. Most diagnostic-quality digital images in CT, MRI, and computed radiography/digital radiography are displayed in 10 or 12 bits.

The file size of an imaging study also depends on the number of images in that study. A chest radiograph may have 2 images (posteroanterior and lateral), whereas a CT scan of the abdomen may have 50 images. With the advent of multidetector row CT scanners, it is now possible to acquire thinner slices in much less time, often resulting in much larger studies. This capability also allows images to be reconstructed in different planes. All of this contributes to an increased number of images and, overall, larger study sizes for storage. A CT angiogram may contain 500 to 1000 images or more.

9. How large are these studies?

Table 5-1 shows approximate matrix and file sizes for various imaging modalities. These values vary depending on bit depth, number of images acquired, and compression technique.

10. What is teleradiology?

Teleradiology is the process of sending digital radiology images over a computer network to a remote location (across town or across the globe) for viewing and interpretation. The American College of Radiology publishes a set of guidelines and standards for teleradiology that include minimal display requirements, security and privacy provisions, and documentation standards.

11. What is IHE?

Integrating the Healthcare Enterprise (IHE) is an initiative undertaken by medical specialists and other care providers, administrators, information technology professionals, and industry professionals to improve the way computer systems in health care share information. IHE promotes coordinated use of established communications standards such as DICOM and HL7 (see question 12) to address specific clinical needs that support optimal patient care. Systems developed in accordance with IHE communicate with one another better, are easier to implement, and enable care providers to use information more effectively.

12. What is HL7?

Health Level 7 (HL7) is the standard used by most RIS and HIS to exchange information between systems. It was designed for sending notifications about events in a health system (e.g., a patient is admitted) and transmitting information (e.g., laboratory data and radiology reports). It was not designed to handle image information, because that role is primarily served by DICOM.

13. How are conventional radiographs integrated into an all-digital PACS?

There are three methods. The first method is to obtain a conventional radiograph on film and digitize the image using a scanner. In fully digital environments, this method is usually reserved for digitizing "outside" films or films from settings where digital acquisition has not yet been implemented, such as in the operating room. The second and third methods for acquiring digital radiographs are computed radiography (CR) and digital radiography (DR).

Table 5-1. Approximate Matrix and File Sizes for Various Imaging Studies

	Image Matrix		*Images*		*File Size (in MB)*	
MODALITY	**X**	**Y**	**AVERAGE**	**RANGE**	**AVERAGE**	**RANGE**
CR	2000	2500	3	2-5	30	20-50
DR	3000	3000	3	2-5	54	40-90
Digital mammography	3000	3000	6	4-8	100	75-150
Multidetector row CT	512	512	500	200-1000	250	100-600
MRI	256	256	200	80-1000	25	10-150
Ultrasonography	640	480	30	20-60	20	10-40
Nuclear medicine	256	256	10	4-30	1	0.5-4
Digital fluoroscopy (without digital subtraction angiography [DSA])	1024	1024	20	10-50	20	10-50
Digital fluoroscopy (with DSA)	1024	1024	150	120-240	450	360-720

14. What is voice recognition (or speech recognition)?

Voice recognition is the process by which a computer system recognizes spoken words and converts them into text. Comprehending human languages falls under a different field of computer science called natural language processing. Early systems required that the speaker speak slowly and distinctly, separating each word with a short pause. These systems were called discrete speech systems. More recently, continuous speech systems have become available that allow the user to speak more naturally.

15. What are the advantages and disadvantages of voice or speech recognition relative to conventional dictation/transcription?

There are several advantages to voice recognition over conventional dictation for radiology reporting. Report turnaround time is vastly reduced, overall cost is decreased (because transcriptionists are no longer required), and users who take advantage of text macros can dictate standard reports in less time.

The disadvantages include erroneous reports because of poor recognition of the speech of certain individuals (sometimes because of lack of training) and difficulty in recognizing similar sounding words (e.g., "hypointense" vs. "hyperintense"). Poor recognition and inefficient use of macros often result in increased dictation time and frustration on the part of the radiologist, which is usually remedied with better training and support.

16. What is structured reporting?

Structured reporting enables the capture of radiology report information so that it can be retrieved later and reused. A key feature of a structured report is consistent organization. A report of an abdominal CT study might follow subheadings that describe each of the anatomic areas listed in the report, such as the liver, spleen, pancreas, and kidneys. This feature of structured reporting is sometimes called "itemized reporting" or "standardized reporting" and is preferred by referring physicians, presumably because specific information can be found more easily than in a narrative report. There are no reliable data on the frequency with which reports of this type are currently used. Structured reports also use standard language.

When defined terms from a standard lexicon are associated with imaging reports, the information in the report becomes more accessible and reusable. For many years, mammography has fostered the use of structured reporting as strictly defined—choosing from a limited set of options, such as the six Breast Imaging Reporting and Data System (BI-RADS) categories, to express the likelihood of cancer on a mammogram. BI-RADS reduces the variability and improves the clarity of communication among physicians. Correlation of the recorded structured data items to histopathologic findings (often performed automatically) provides regular feedback to radiologists on their strengths and weaknesses, improving the overall quality of mammographic interpretation.

17. What is RadLex?

RadLex is a comprehensive lexicon for the indexing and retrieval of online radiology resources developed by the Radiological Society of North America (RSNA) and other radiology organizations, including the American College of Radiology (ACR). It has been designed to satisfy the needs of software developers, system vendors, and radiology users by adopting the best features of existing terminology systems, while producing new terms to fill critical gaps. RadLex also provides a comprehensive and technology-friendly replacement for the ACR Index for Radiological Diagnoses. Rather than "reinventing the wheel," RadLex unifies and supplements other lexicons and standards, such as SNOMED-CT and DICOM.

18. What is CADe?

CADe stands for computer-aided detection, a computerized system that identifies portions of an image that may correlate to abnormalities, utilized to decrease perception error and reduce false negative rates. The FDA has approved the use of CADe for mammography, chest radiography, chest CT, and CT colonography. This is not to be confused with CADx (or CAD), which is computer-aided diagnosis. CADe of a finding requires validation by a radiologist, whereas CADx presumes independent clinical diagnosis of a disease.

19. What is BI-RADS?

Breast Imaging Reporting and Data System (BI-RADS) is a standard lexicon developed by the ACR used for reporting mammography findings in addition to breast ultrasonography and MRI findings.

20. What types of injuries can result from working at a PACS workstation, and what are some potential remedies?

Repetitive stress symptoms have been reported in the literature as being highly prevalent among radiologists working in PACS-based environments. Compared to film reading environments, PACS-based environments and electronic workstations have important factors that directly affect comfort and, therefore, performance, including seating, heat, noise, and light. For example, cubital tunnel syndrome may result from compression of the ulnar nerve at the medial elbow due to prolonged elbow flexion or extrinsic pressure. Having a padded chair arm rest and a hands-free dictation microphone can help prevent this syndrome. Additional interventions including use of an ergonomic mouse, adjustable chairs, workstation tables, and educational training have resulted in improved symptoms. With the advent of filmless interpretation, growing concerns regarding repetitive stress symptoms have prompted some radiology departments to implement ergonomic solutions.

21. What is image sharing?

Image sharing refers to the electronic exchange of patient medical images between hospitals, physicians, and patients. While past image sharing has depended largely on physical media, predominantly compact discs (CDs), there has been a recent push from the National Institutes of Health (NIH) to develop an image exchange method without relying on physical media. In response, the RSNA has developed an Image Share Network (ISN) based on the XDS.I.b profile of IHE. The ISN is essentially a secure web-based network that has been piloted to several institutions nationwide and allows for both physician and patient access to medical images.

Image sharing has become increasingly important. Benefits of image sharing include potentially improved interpretative quality given the availability of a prior imaging study for comparison, decreased numbers of inappropriately ordered or duplicated exams with associated decreased radiation exposure, shared diagnostic information for improved patient care by multiple care providers for the same patient, and timely availability of images or results at the point of care.

Challenges to optimal image sharing include concerns regarding privacy and security, given the use of protected health information, in addition to competitive concerns by health care institutions across the board. Having a high-security Health Insurance Portability and Accountability Act (HIPAA)-compliant data hosting center is necessary, and strict standards must be met to be HIPAA certified. Features that are secure and compliant include proper ability for identification and authentication, authorized privileges, access control, confidentiality, integrity of data, and accountability with audit trails. Other challenges include bandwidth requirements necessary for the image sharing network, which requires significant investment.

22. What is XDS?

XDS, which stands for cross-enterprise document sharing, helps manage access of patient electronic health records across health enterprises, by creating a standard set of specifications to enable sharing of medical documents between enterprises. XDS assumes that enterprises belong to an XDS affinity domain, which is a group of health care enterprises with shared policies usually bound through legal agreements. Four systems for mediating sharing of data within the XDS profile include the document repository, document registry, document source, and document consumer. Exchange of data itself takes place through XDS transactions. Key transactions include a provider/register document set, a registry stored query, and retrieval of the document set. XDS-I is an extended profile with new specifications optimized specifically for medical imaging.

23. What is Imaging 3.0?

Imaging 3.0 is a model framework for the evolution of radiology, created by the ACR, for the purpose of optimally equipping radiologists for value-based health care and a more active role in patient care. Imaging 3.0 principles are suggested at every decision making point in the delivery of imaging care, including steps prior to and following interpretation, by utilizing proper information technology systems and processes. Principles of Imaging 3.0 affect security and privacy, workflow processes, business intelligence analytics, clinical decision support, dose and safety, education and training qualifications, image acquisition, archiving and retrieval, image display, reporting and communication, transmission and communication, RIS/EMR integration, and communication with mobile devices.

24. What factors are important to consider when choosing a mobile device for use in radiology departments?

Mobile devices have become integral to everyday life. To operate within a secure and optimal environment within radiology, multiple aspects must be considered. The main factors include:

- Security: Access to the device, communication with other devices via Wi-Fi or cellular networks, and HIPAA compliance.
- Bandwidth: Important for data transfer speeds.
- Screen resolution: Radiographs are usually the largest images in terms of pixel number, with the exception of mammograms, for which a full-resolution image ranges from 4 to 12 megapixels (MPs).
- Display size: Typical desktop PACS displays are about 21 inches diagonally, tablet displays are about 10 inches, and phone displays are about 3.5 inches. Display size of a phone is currently too small to adequately view a radiographic image. For CT, MR, ultrasonographic, and nuclear medicine images, the smartphone display is likely adequate for an on-call scenario, although daily use is not likely practical at this time.
- Pixel pitch: Length of one side of a square pixel, which ranges from 270 microns for low-resolution desktop displays to 78 microns for the latest iPhones with "retina display." Increased pixels lead to increased information in a fixed area, but pixels must at least be at the threshold of human perception.
- Luminance: Brightness, which affects ability to discriminate contrast in radiologic images. Mobile devices have output luminances currently of 400 to 500 cd/m2, on par with desktop medical displays. Given the automated power management features on many mobile devices to dim the display in certain settings, display dimming must be checked for and prevented on the viewing application.

25. Can I interpret radiology images on a tablet device?

Many radiology applications for image viewing are labeled "not for diagnostic interpretation." However, there are FDA-approved applications for interpreting images on a mobile device "when no dedicated workstation is available." Under the FDA, "a mobile application that displays radiological images for diagnosis transforms the mobile platform into a class II Picture Archiving and Communications Systems (PACS)." These are subjected to regulatory oversight and

considered regulated medical devices which must comply with device classifications associated with the transformed platforms.

26. What are the display requirements for diagnostic interpretation of radiology images?

Display requirements include luminance response, pixel pitch, and display size.

- Luminance response: Brightness and contrast of gray scale medical images result from luminance related to image gray level values.
- Maximum luminance: Perceived contrast of image depends on ratio of luminance (LR) for maximum gray value (L_{max}) to luminance of lowest gray value (L_{min}). Note that this is different from the contrast ratio often reported by monitor manufacturers. All display devices in one facility should have the same LR.
- L_{max} of diagnostic monitors should be at least 350 cd/m^2, although monitors for interpretation of mammograms should have L_{max} of at least 420 cd/m^2. Monitors for other purposes should have L_{max} of at least 250 cd/m^2.
- DICOM gray scale display function (GSDF) should be used to set intermediate gray values with similar response functions among all monitors in a facility.
- Calibration: Luminance response, LR, and GSDF can be selected using the monitor on-screen display controls, although some devices may require software from the monitor manufacturer to set luminances of each gray level.
- Quality control: Display devices should be periodically checked to verify the luminance response. Both basic and advanced verification tests may be utilized. Contrast response of monitors for diagnostic interpretation should be within 10% of the GSDF over the full LR and the contrast response should be within 20% of the GSDF over the full LR for other purposes.
- Pixel pitch: Spacing of pixel structures, which determines amount of detail that can be presented. Determines maximum spatial frequency that can be presented in an image. The maximum spatial frequency that can be described by digital signals with a constant pitch P is 1/(2P) cycles/mm. Optimal pixel pitch should be small to present all spatial frequencies within human visual perception. The pixel pitch should be about 0.200 mm but not larger than 0.210 mm for diagnostic interpretation.
- Display size: Visualization of the full scene is optimal when the diagonal display distance is about 80% of the viewing distance, which corresponds to approximately 21 inches (53 cm) when there is an arm's length viewing distance of about 60 cm. An aspect ratio (width to height) of 3 : 4 or 4 : 5 works well for presentation of radiographic images.

27. Where can I learn more about imaging informatics? Are there formal training programs and certifications available?

- The Society for Imaging Informatics in Medicine (SIIM) is a health care organization involved in advancing the field of imaging informatics, with the overarching goal to improve quality and delivery of patient care. SIIM has a plethora of online resources (http://siim.org) and online educational content for both newcomers and veterans in the field of informatics.
- Fellowships are available and growing for those interested in advancing their informatics skills. A list of current imaging informatics fellowship programs is available at http://siim.org/about/fellows/imaging-informatics-fellowships.
- The RSNA has information about informatics (http://www.rsna.org/Informatics.aspx) with links to IHE, the RSNA Teaching File System, RSNA Image Share, and RadLex in addition to information about Meaningful Use, reporting templates, and more.
- The ACR has online resources about informatics including in-depth reference guides created by the Information Technology (IT) and Informatics Committee in collaboration with the Quality and Safety Commission (http://www.acr.org/Advocacy/Informatics).
- The American Board of Imaging Informatics (https://www.abii.org) is a nonprofit organization that sets the professional certification standards for candidates interested in becoming a Certified Imaging Informatics Professional (CIIP) through a formal training pathway. The American Medical Informatics Association (AMIA) is an organization for leading informatics professionals throughout all of medicine and the health care industry (http://www.amia.org).
- The Healthcare Information and Management Systems Society (HIMSS) is a nonprofit organization for health through information technology (http://www.himss.org).

KEY POINTS

- Image storage size is determined by spatial resolution and bit depth, and storage size of an imaging examination is determined by image storage size and the total number of images.
- The Digital Imaging and Communications in Medicine (DICOM) standard is currently used to allow medical images and associated information to be exchanged between imaging equipment from different vendors, computers, and hospitals.
- The picture archiving and communication system (PACS) is used to store and display medical images.

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CHAPTER 6

INTRODUCTION TO CONTRAST AGENTS

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1. What is a radiographic contrast agent?

A radiographic contrast agent is a substance that is administered to a patient during an imaging examination to improve its diagnostic performance. Contrast agents are most often administered via the intravenous (IV) and oral routes for computed tomography (CT) and magnetic resonance imaging (MRI) examinations. However, other routes of contrast administration may be utilized, depending on the particular imaging study to be performed. For example, arteriography requires the intraarterial (IA) administration of contrast material, while arthrography requires the intraarticular injection of contrast material directly into a joint. Intrathecal contrast administration is required for myelography.

A catheter is used to inject the contrast material in some procedures. In hysterosalpingography, a catheter or cannula is placed into the external cervical os to opacify the uterine cavity. In retrograde urethrography, a Foley catheter is placed at the urethral meatus in a male to inject contrast material to evaluate the urethra. In cystography, injection of contrast material is performed through a catheter placed in the urinary bladder. In retrograde pyelography, contrast material is administered through catheters placed into the renal collecting systems with cystoscopic guidance to evaluate the pyelocalyceal systems and ureters in patients who cannot receive intravenous contrast material.

The administration of radiographic contrast agents by the various routes mentioned above is widely used in clinical practice, and is usually not associated with any adverse effects. However, prior to administering contrast material, attention must be given to the clinical indication for the procedure, and to the clinical status of the patient in order to minimize adverse side effects and to maximize diagnostic yield. It is essential that in a facility where contrast material is routinely administered for imaging studies, trained personnel along with appropriate equipment and medications be available on site to manage a contrast reaction, should one occur.

2. What types of contrast agents are available for intravascular use?

Iodinated contrast agents are used in all studies where x-rays are utilized, such as CT, intravenous urography (IVU), and all fluoroscopic studies. These can be broadly classified based on osmolality (high, low, or iso-), ionicity (ionic or nonionic), and the number of benzene rings in the chemical structure (monomeric or dimeric). Nonionic contrast agents are associated with less discomfort during intravascular administration and fewer adverse reactions compared to ionic contrast agents. Therefore, nonionic low osmolal or iso-osmolal contrast agents are almost exclusively used in current clinical practice for intravascular injections, particularly in developed countries.

Gadolinium-based contrast agents are used in MRI studies and can be classified based on ionicity (ionic or nonionic), the chelating ligand (macrocyclic or linear), and the pharmacokinetics (extracellular or organ specific). Ionic and nonionic agents have relatively little or no difference in acute reactions and discomfort.

There are other types of intravascular contrast agents, such as iron oxide–based contrast agents that are used in MRI studies and microbubble contrast agents that are used in ultrasonography (US) studies; these will not be discussed because they are beyond the scope of this chapter.

3. How common are acute adverse reactions to intravascular contrast material?

Acute adverse events occur in up to 0.7% of patients who receive intravascular low or iso-osmolality iodinated contrast material, and in up to 0.04% of patients who receive gadolinium-based contrast material.

Most adverse reactions to contrast agents are mild and not life-threatening, usually requiring only observation, reassurance, and/or supportive measures. Severe and potentially life-threatening adverse events occur rarely and unpredictably, most often within the first 20 minutes following contrast administration.

4. What are the categories of acute adverse reaction to contrast agents?

Allergic-like reactions, rather than true allergies, are seen with radiographic contrast administration and are referred to as anaphylactoid reactions. These are not true hypersensitivity reactions, and immunoglobulin E (IgE) antibodies are not involved. The clinical manifestations may be similar to allergic reactions (such as hives or bronchospasm), but these reactions are often idiosyncratic and prior sensitization is not required, unlike with true allergies. These reactions are independent of the dose and concentration of the contrast agent. A history of prior allergic-like contrast reaction may indicate the need for corticosteroid premedication prior to future contrast-enhanced studies that utilize a similar contrast agent.

Physiologic reactions to contrast agents are associated with the dose, molecular toxicity, and physical and chemical characteristics of the contrast agent. A history of a prior physiologic contrast reaction does not indicate the need for future corticosteroid premedication.

For a detailed classification of acute adverse reactions to contrast agents, see Table 6-1.

Table 6-1. Classification of Acute Contrast Reactions

SEVERITY	ALLERGIC-LIKE	PHYSIOLOGIC
Mild: self-limited symptoms and signs	Limited urticaria/pruritus Limited cutaneous edema Limited "itchy"/"scratchy" throat Nasal congestion Sneezing/conjunctivitis/rhinorrhea	Limited nausea/vomiting Transient flushing/warmth/chills Headache/dizziness/anxiety/altered taste Mild hypertension Vasovagal reaction that resolves spontaneously
Moderate: more pronounced symptoms and signs, potentially becoming severe if untreated	Diffuse urticaria/pruritus Diffuse erythema, stable vital signs Facial edema without dyspnea Throat tightness or hoarseness without dyspnea Wheezing/bronchospasm, mild or no hypoxia	Protracted nausea/vomiting Hypertensive urgency Isolated chest pain Vasovagal reaction that requires and is responsive to treatment
Severe: often life-threatening, potentially resulting in permanent morbidity or death if not managed appropriately	Diffuse edema, or facial edema with dyspnea Diffuse erythema with hypotension Laryngeal edema with stridor and/or hypoxia Wheezing/bronchospasm, significant hypoxia Anaphylactic shock (hypotension and tachycardia) Pulmonary edema Cardiopulmonary arrest	Vasovagal reaction resistant to treatment Arrhythmia Convulsions, seizures Hypertensive emergency Pulmonary edema Cardiopulmonary arrest

5. What are the 5 important immediate assessments that should be made when evaluating a patient for a potential contrast reaction?

1. How does the patient look (e.g., level of consciousness and appearance of the skin)?
2. How does the patient's voice sound? Can the patient speak?
3. How is the patient's breathing?
4. What is the patient's pulse strength and rate?
5. What is the patient's blood pressure?

For full details regarding the treatment algorithms for acute contrast reactions, which are beyond the scope of this chapter, please see the American College of Radiology (ACR) Manual on Contrast Media (http://www.acr.org/quality-safety/resources/contrast-manual).

6. What are some risk factors that predispose patients to acute adverse contrast reactions?

- Prior allergic-like reaction to contrast material. (Patients with a history of prior severe contrast reaction have an ≈5- to 6-fold increased risk of a future contrast reaction.)
- History of severe allergies or reactions to other agents (food or medications), especially when to multiple agents.
- History of asthma, bronchospasm, or atopy.
- History of cardiac or renal disease.

7. When do adverse reactions to intravascular iodinated contrast material usually occur?

Most reactions to intravascular iodinated contrast occur within 1 hour of intravenous administration. However, delayed adverse reactions may occasionally occur between 1 hour and 1 week following contrast administration. Such delayed reactions are seen more commonly in young adults, women, and patients with a history of allergy, are most commonly cutaneous (e.g., urticaria, rash, or angioedema), and are typically mild to moderate in severity and self-limited. The incidence of delayed allergic-like reactions has been reported to range from 0.5% to 14% and may occur more commonly with iso-osmolal dimeric contrast agents.

8. What is iodine "mumps"?

Iodine "mumps" is sialoadenopathy or salivary gland swelling that may rarely occur in delayed fashion following iodinated contrast administration.

9. When is premedication indicated prior to contrast administration?

The primary indication for premedication prior to contrast-enhanced imaging is the pretreatment of patients at increased risk for an acute allergic-like reaction to contrast material. Premedication generally involves the administration of corticosteroids, sometimes in conjunction with H1 blockers.

At our institution, indications for premedication include:

- Prior moderate or severe allergic-like reaction to contrast material.
- Prior intravenous contrast reaction requiring administration of epinephrine.
- Prior life-threatening reaction to any allergen or medication.

- Presence of asthma with active wheezing.
- Presence of asthma requiring intubation in the last 3 months.

10. What is a breakthrough reaction?

A breakthrough reaction is a repeat contrast reaction that occurs in a premedicated patient. Breakthrough reactions are most often similar to the index reaction in terms of severity and clinical presentation. Presence of severe allergies to any other substance, more than four allergies, any drug allergy, and chronic use of oral corticosteroids are associated with a higher risk of a moderate or severe breakthrough reaction.

11. Is there a specific association between presence of a shellfish allergy and an increased allergy to iodinated contrast material?

It is an incorrectly held perception in clinical practice that shellfish allergy specially predisposes patients to contrast reaction. An allergy to shellfish does not increase the risk for an adverse reaction to iodinated contrast material any more than do other allergies.

12. Is there a specific association between presence of an allergy to iodinated contrast material and having a future reaction to gadolinium-based contrast material?

Although there is no cross-reactivity between iodinated and gadolinium-based contrast agents, patients with a history of previous reaction to iodinated contrast material have an increased risk of acute reaction to gadolinium-based contrast material.

13. How often does extravasation of intravenous contrast material occur?

Extravasation of intravenous contrast material (i.e., when administered contrast material escapes the vascular lumen and infiltrates the interstitial tissue at the site of injection) may occur in up to 0.9% of patients following intravenous administration of iodinated contrast material. Extravasation is less commonly encountered following intravenous gadolinium-based contrast administration, because the injected contrast volumes are much lower (typically <20 ml) compared to those studies utilizing iodinated contrast material (typically 100 ml). Most extravasations are limited to the superficial (skin and subcutaneous) soft tissues, and may either be asymptomatic or associated with soft tissue swelling, tightness, pain, or tenderness. However, most contrast extravasations resolve without incident following conservative management with elevation of the extremity and application of warm or cold compresses.

14. What is the most common severe injury that may occur following extravasation of intravenous contrast material?

Acute compartment syndrome is the most common severe injury following intravenous contrast extravasation. This is an extremely rare complication, which occurs when the tissue pressure within a closed muscle compartment exceeds the perfusion pressure secondary to the increased fluid content, leading to muscle and nerve ischemia. It is more likely to occur after the extravasation of a large volume of contrast material, particularly when located in less capacious/distensible areas of the extremity such as the hand, wrist, or forearm.

If there is clinical evidence for a severe extravasation injury such as progressive swelling or pain, altered tissue perfusion as manifested by a decreased capillary refill, change in sensation in the affected limb, or skin ulceration or blistering, then immediate surgical consultation is indicated. Compartment syndrome is typically treated with decompressive fasciotomy.

15. What is contrast-induced nephropathy (CIN)?

CIN is a deterioration in renal function that is caused by intravascular iodinated contrast administration. It occurs uncommonly, and its exact pathophysiology is not understood. CIN is most commonly defined as either an absolute (≥0.5 mg/dL) or relative (≥25%) increase in serum creatinine levels compared to baseline levels within 48 to 72 hours following the intravascular administration of iodinated contrast material, which is not attributable to other causes. Serum creatinine usually begins to increase within 24 hours of contrast administration, peaks within 4 days, and often returns to baseline within 7 to 10 days.

16. What are the major risk factors for CIN?

Preexisting severe renal insufficiency is the most important risk factor. Other risk factors may include advanced age, dehydration, diabetes mellitus, hypertension, cardiovascular disease, multiple myeloma, hyperuricemia, and administration of multiple doses of iodinated contrast material within a 24-hour period.

17. What is the best way to prevent CIN?

Patient hydration is the simplest and most effective action to prevent CIN in patients who will receive intravascular iodinated contrast material. Otherwise, the simplest and most effective action is to avoid administration of intravascular iodinated contrast material.

18. Does metformin increase the risk of CIN?

No. Metformin, an oral antihyperglycemic drug often used to treat non-insulin-dependent diabetes mellitus, does not confer an increased risk of CIN. However, patients taking metformin who develop renal insufficiency following intravascular iodinated contrast administration may be at increased risk to develop lactic acidosis. Therefore, metformin is temporarily discontinued prior to contrast administration, withheld for 48 hours after contrast administration, and reinstituted only after renal function has been reassessed and found to be normal.

19. Which factors require assessment of patient renal function prior to administration of intravascular contrast material?

- Patient age >60
- History of renal disease, including:
  - Dialysis
  - Renal transplant
  - Single kidney
  - Renal cancer
  - Renal surgery
- History of hypertension requiring medical therapy
- History of diabetes mellitus
- Metformin or metformin-containing drug combinations (for iodinated contrast material administration only)

At our institution, when the serum creatinine level is ≤1.4 mg/dL, iodinated contrast material can be administered, assuming that there are no other contraindications. When the serum creatinine level is between 1.5 and 1.9 mg/dL or rising, iodinated contrast material can still be administered, but only after a conversation with the referring physician has taken place to discuss the risks and benefits of administering contrast material and possible diagnostic test alternatives. When the serum creatinine level is ≥2.0 mg/dL, iodinated contrast material is generally not administered unless there is an urgent medical necessity.

20. What are the major contraindications to the administration of intravascular contrast material?

- Patient refuses to receive intravascular contrast material.
- Patient did not receive premedication, when indicated, prior to scheduled contrast administration.
- Patient has renal insufficiency.
- Patient has thyroid disease that will be treated with systemic ^{131}I radiotherapy. This contraindication applies for iodinated, not gadolinium-based, contrast material only. The reason is that iodinated contrast material transiently decreases ^{131}I radiotracer uptake in the thyroid gland, potentially decreasing the effectiveness of subsequent radioiodide therapy.
- Patient is pregnant. This contraindication particularly applies for the intravascular administration of gadolinium-based contrast material.

21. Can intravascular iodinated contrast material be safely administered to anuric patients with end-stage renal disease who are on dialysis?

Yes, patients with anuric end-stage chronic renal disease who do not have a functioning renal transplant can receive intravascular iodinated contrast material without risk of further renal damage, given that the kidneys are no longer functioning. Early postprocedural dialysis is not supported by expert guidelines; the volume of intravenous contrast material may add to fluid overload and should be included in the fluid intake of such patients.

However, there is a potential risk of converting an oliguric patient on dialysis to an anuric patient on dialysis following contrast administration, although this is somewhat speculative.

22. What is nephrogenic systemic fibrosis (NSF), and who is at risk for developing this complication?

NSF is a rare systemic fibrotic disorder that primarily involves the skin and subcutaneous tissues, but it can also affect other organs including the lungs, pleura, pericardium, skeletal muscle, and internal organs. It occurs in patients with severe acute or chronic renal dysfunction, including patients who are receiving dialysis of any form, and in many cases is believed to be secondary to the release of free gadolinium (Gd^{3+}) ions from the chelates that constitute gadolinium-based contrast agents, with subsequent deposition of insoluble gadolinium phosphate precipitates in bodily tissues. As the contrast agents are metabolized through the renal system, they have a prolonged half-life in patients with decreased renal function, increasing the likelihood that gadolinium release and deposition in tissues will occur. However, NSF can occur without exposure to gadolinium-based contrast agents.

When NSF is associated with gadolinium-based contrast agents, it usually manifests within 2 to 10 weeks following contrast administration. The risk of NSF may be related to the specific type of contrast agent, the cumulative dose, and the residual renal function of the patient. Macrocyclic gadolinium-based contrast agents are the most stable ones and are associated with the lowest risk of NSF, followed by linear ionic and linear nonionic agents in order of decreasing stability and associated increased risk of NSF.

NSF has a high morbidity and mortality rate and has no known uniformly effective treatment. Therefore, patients who are planning to undergo MRI with gadolinium-based contrast agents must be carefully screened for renal dysfunction. When the estimated glomerular filtration rate (eGFR) is ≥60 mL/min/1.73m^2, gadolinium-based contrast material can be administered as indicated, assuming there are no other contraindications. When the eGFR is 30 to 59 mL/min/1.73m^2, a macrocyclic gadolinium-based contrast material can be administered using the lowest possible dose. When the eGFR is <30 mL/min/1.73m^2, gadolinium-based contrast material is generally not administered unless there is an urgent medical necessity.

23. Is intravascular iodinated contrast material contraindicated for use in pregnant women?

No. Even though iodinated contrast material crosses the blood-placental barrier and enters the fetus, there have been no reports of neonatal hypothyroidism or teratogenic effects following maternal intravascular administration of iodinated contrast material.

Because there are no available data to suggest any potential harm to the fetus from exposure to intravascular iodinated contrast administration, iodinated contrast material can be administered to pregnant or potentially pregnant patients when needed for diagnostic purposes. A more important consideration in pregnancy is the risk of radiation exposure to the fetus from imaging studies.

24. Is intravascular gadolinium-based contrast material contraindicated for use in pregnant women?

Yes. Gadolinium-based contrast material is assumed to cross the blood-placental barrier and enter the fetus. Although there have been no known adverse effects to fetuses following maternal intravascular gadolinium-based contrast administration, no well-controlled studies of the teratogenic effects of gadolinium-based contrast material in pregnant women have been performed. Yet, teratogenic effects have been shown in animal studies following intravascular administration of high and repeated doses of gadolinium-based contrast material. Furthermore, gadolinium chelates may accumulate in the amniotic fluid with potential for release of free gadolinium (Gd^{3+}) ions, potentially conferring a risk for the development of NSF in the mother or fetus.

Because it is unclear how gadolinium-based contrast material will affect the fetus, gadolinium-based contrast material is contraindicated for use in pregnant women, and it is used only with extreme caution in rare cases following informed patient consent when there is a potential significant benefit to the patient or fetus that outweighs the possible but unknown risk to the fetus.

25. Is intravascular contrast material safe for use in women who are breast-feeding?

Yes. Less than 1% of administered iodinated contrast material or gadolinium-based contrast material is excreted in breast milk, and <1% of the contrast material ingested by infants through breast-feeding is absorbed through the gastrointestinal tract. Furthermore, direct toxicity or allergic sensitization or reaction in infants to absorbed contrast material has not been reported. If the mother has concerns about any potential ill effects to her infant, she may express and discard breast milk for 12 to 24 hours after having received contrast material. In anticipation of this, the mother may use a breast pump to obtain and save breast milk during the 24 hours prior to receiving contrast material.

26. What major types of enteric contrast agent are available?

Barium sulfate enteric contrast agents (predominantly used in gastrointestinal fluoroscopic and CT studies) are utilized for distention and opacification of the gastrointestinal tract and may be administered by mouth, per rectum, via an ostomy, or via an indwelling bowel catheter. Iodinated enteric contrast agents can alternatively be utilized to distend and opacify the bowel.

27. What are the major complications of barium sulfate enteric contrast material?

Leakage of barium sulfate enteric contrast material from the bowel into the mediastinum or peritoneal cavity can lead to mediastinitis or peritonitis, respectively. As such, when bowel perforation is suspected or known to exist, iodinated water-soluble enteric contrast material, rather than barium sulfate enteric contrast material, is administered.

Aspiration of large volumes of barium sulfate contrast material can lead to acute respiratory distress or pneumonia.

Adverse reactions to barium sulfate enteric contrast material can occur but are rare and are almost always mild.

28. What are the major complications of iodinated contrast material when used as an oral contrast agent?

Aspiration of high-osmolality iodinated oral contrast material can lead to life-threatening pulmonary edema. As such, in patients at high risk for aspiration, this can be mitigated or prevented by use of low or iso-osmolal iodinated oral contrast material or by use of barium sulfate enteric contrast material.

Approximately 1% to 2% of iodinated enteric contrast material is absorbed and subsequently excreted into the urinary tract. Adverse reactions to iodinated enteric contrast material are rare but can be moderate or severe, particularly in patients with a history of prior reaction to intravascular contrast material, as well as in those with active inflammatory bowel disease, where there may be increased enteric absorption of contrast material.

KEY POINTS

- A history of a previous severe reaction to a contrast agent increases the overall risk for a subsequent contrast reaction by ≈5- to 6-fold.
- Distinguishing physiologic from allergic-like contrast reactions is important because patients with physiologic reactions do not require future corticosteroid premedication, whereas those with allergic-like reactions may need future corticosteroid premedication.
- Patient hydration is the simplest and most effective action to prevent CIN in patients who will receive intravascular iodinated contrast material.
- If there is clinical evidence for a severe extravasation injury, then immediate surgical consultation is indicated.
- Intravascular gadolinium-based contrast material is contraindicated for use in pregnant patients. However, iodinated contrast material can be administered to pregnant or potentially pregnant patients when needed for diagnostic purposes.