Practical Imaging Informatics

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Foundations and Applications for PACS Professionals

SIIM
SOCIETY FOR
IMAGING INFORMATICS IN MEDICINE
INNOVATING IMAGING INFORMATICS

Springer

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For the four who laid the flagstones
And the three who walk behind,
Eyes wide with wonder

And for Cara
Always for Cara

BFB

To my wife Terry, a font of affection and inspiration.

DLR

This book is dedicated to my family, your love and support strengthens me. Philippians 4:13.

DSG

To my wife Janet, for her transcendent love, encouragement, and support.

DLW

The Editors are indebted to Ms. Caroline Wilson; without her tireless efforts, this book never would have come to fruition.

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Introduction

Barton F. Branstetter IV

The Evolution of the Imaging Informatics Professional

Within the last decade, medicine has undergone a dramatic transformation to a digital environment. Radiology has been at the leading edge of this change, with Picture Archiving and Communication Systems (PACS) becoming almost ubiquitous across the United States. As PACS developed and matured and became a mission-critical component of patient care, radiologists realized that a dedicated team of individuals would be needed to ensure that the PACS functioned continuously and reliably.

But where to find these individuals? A strong computer background would be essential, but a computer programmer or IT professional might not understand the clinical needs that underlie the PACS. After all, most IT systems do not require support that is timely and urgent, with patient-care decisions hanging in the balance. Changing from the IT culture to the medical culture can be difficult. So, a clinical background (e.g., technologists, nurses) is also critical. But relatively few people in these careers had the computer background to maintain a system as complex as a PACS. Even fewer had an interest in switching to an untested and uncertain career path.

Thus was born the PACS administrator – that rare breed with knowledge of both clinical workflow and information technology. Unfortunately, there were not enough people with the requisite skills to fill these roles. A few motivated, self-taught individuals from a variety of backgrounds found ways to fill the gaps in their own knowledge and become a bridge between the clinical and IT communities.

As PACS evolved, so did the training and background required of a PACS administrator. Keeping the PACS working was no longer sufficient – the ability to improve the PACS, work with the vendors, and even make the PACS communicate with other IT infrastructure in the hospital became critical to the job. Other specialties outside of radiology began to need similar services, and the obvious person to play that role was the PACS administrator.

But, this transition was not easy. Not only was the traditional training inadequate, the terminology describing the job was also inadequate. Seeing that the knowledge base developed in radiology was becoming needed throughout the medical enterprise, the Society for Computer Applications in Radiology transformed itself into the Society for Imaging Informatics in Medicine, and the PACS administrator was transformed into the Imaging Informatics Professional (IIP), who has responsibilities far beyond the boundaries of the PACS itself.

With the new terminology, the core knowledge needed for the job had widened. The clinical knowledge base had widened to include medical specialties outside of radiology, and the IT knowledge base required an understanding of software interactions and networking across the entire enterprise. Who can fill this role? Who has the skills and knowledge to do the job? How can employers be sure that applicants for an IIP position will be able to serve the physicians and patients who are the ultimate clients of the digital infrastructure?

That is where certifying organizations such as the American Board of Imaging Informatics (ABII) come in. This organization, and others like it, was created to certify individuals from varying backgrounds in IT and clinical care, and to ensure that everyone who calls themselves an IIP has the knowledge and skills needed not just to keep the PACS afloat but also to keep the entire medical imaging infrastructure running smoothly, and improve efficiency for the whole medical enterprise.

Who Should Read This Book

The primary audience for this book is Imaging Informatics Professionals (and those who want to become IIPs). A certification test, such as the Certified Imaging Informatics Professional (CIIP) test offered by the ABII, is certainly a good reason to master the wealth of information in this book! But, it is worth noting that this book, like all educational programs offered by the Society for Imaging Informatics in Medicine (SIIM), is independent of the ABII and the CIIP certification program. The authors of this book do not have any inside information about the CIIP test.

Hopefully, this book will also be useful to IIPs long after the test is completed and passed, as a reference and troubleshooting guide for everyday imaging informatics. The layout and format of the book are designed with one major purpose in mind: quick reference. Our goal was to make sure that anyone who had read the book could look up a critical piece of information in the minimum amount of time. If you flip to the correct chapter, the key words and key concepts should jump out at you, and hopefully, the information you need should be right there, easy to find. Important definitions, checklists, and concepts are set off in color-coded boxes that draw the reader's eye. Sources of additional information are clearly highlighted. IIPs are masters of workflow efficiency, so the textbook that supports them had better be efficient to use!

Although IIPs are the primary audience for this book, other professionals will hopefully find it useful. IT staff working in medicine, even if not in the formal role of PACS administrator, will benefit from understanding the clinical references that pervade their work. Physicians and trainees interested in informatics will find the information pertinent to their practice, and the knowledge base formed by reading this book can serve as a basis for more in-depth study. Administrators supervising or hiring IIPs may also find the book of use, to better communicate with those who are maintaining the digital infrastructure.

The Organization of This Book

The book is divided into six sections. The first two sections are the foundations sections, in which the basics of information technology and clinical image management are introduced. Depending on your background, some of these chapters may seem overly simplistic. The goal of these sections is to bring everyone up speed on areas of knowledge that they might not bring with them from their previous fields of study.

The third and fourth sections of the book are devoted to daily operations – the issues that arise on a day-to-day basis for IIPs, like customer relations and downtime procedures. These sections also contain chapters about the clinical environment in which images are used and interpreted.

The fifth and sixth sections deal with administrative issues that arise less frequently, but have a major impact on the life of the IIP. Decisions such as choosing a PACS vendor and long-range strategic planning fall into these sections of the book.

The field of imaging informatics is rapidly changing. As with all technological fields, newer and better software and solutions are continually developed. No printed textbook can be completely current or exhaustive on topics such as these. The purpose of this book is to answer commonly asked questions and provide a basis for continuous learning. To this end, many of the suggested readings in the chapters are links to websites that are likely to be updated as technology improves.

It is important to remember that every hospital or imaging site is unique. Solutions that work in one location may be totally inappropriate for other enterprises, or even elsewhere within the same enterprise. But some shared themes run through all of medical imaging; hopefully, we have focused on those in this book.

The bottom line – our main goal – was to provide pertinent information to IIPs at the point when it matters most (in medical terminology, “support at the point of care”). With this book at your desk, you should be able to rapidly find the information you need to troubleshoot urgent situations – the sorts of situations faced every day by Imaging Informatics Professionals.

Part I
Technology: Getting Started

Associate Editor: Daniel L. Rubin

Chapter 1
Medical Imaging Modalities and Digital Images

Katherine P. Andriole

Contents

1.1 Introduction

1.1.1 Special Aspects of Medical Images

Medical imaging technologies enable views of the internal structure and function of the human body. Information obtained from the various modalities can be used to diagnose abnormalities, guide therapeutic procedures, and monitor disease treatment. Medical images have unique performance requirements, safety restrictions, characteristic attributes, and technical limitations that often make them more difficult to create, acquire, manipulate, manage, and interpret. Some of these contributing factors include

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> **Definition 1.1: Artifact**
>
> Any component of the image that is extraneous to the representation of tissue structures; can be caused by a technique, technology, hardware, or software error.

- Complexity of imaging situations due to equipment size and available space, inaccessibility of the internal structures of the body to measurement, patient positioning, patient illness, and procedure practicality.
- **Variability** of the data between patients; for example, between normal and abnormal anatomy and physiology, within normal range, and within the same patient at different times or body positions.
- Effect of imaging transducer on the image, including artifacts created by the imaging method or by something in the patient's body. **A major source of artifact in images of living systems is motion**.
- Safety considerations, patient discomfort, procedure time, and cost–benefit tradeoffs.

1.1.2 Medical Imaging Terminology

- **Medical Imaging Hierarchy: Patient – Examination (Study) – Series (Sequence) – Image**. For example, a patient may undergo an imaging examination, also called a study, such as computed tomography (CT) of the abdomen. This study may include several sequences or series, such as the set of images with and the set without contrast. A sequence or series may consist of a single image or multiple images.
- Modalities can be characterized by whether their energy source uses **ionizing radiation** such as for radiography, fluoroscopy, mammography, CT, and nuclear medicine or non-ionizing radiation such as for ultrasound and magnetic resonance imaging (MRI).
- **Projection** (planar) imaging, such as projection radiography in which X-rays from a source pass through the patient and are detected on the opposite side of the body, produces a simple two-dimensional (2-D) shadow representation of the tissues lying between the source and the detector. Each point in the image has contributions from all objects in the body along a straight line trajectory through the patient. Overlapping layers of tissues can make planar imaging difficult to interpret.
- **Tomographic** (cross-sectional) imaging modalities include CT, MRI, and ultrasound. In CT, for example, the X-ray source is tightly collimated to

> **Definition 1.2: Ionizing Radiation**
>
> Radiation capable of producing energetic charged particles that move through space from one object to another where the energy is absorbed; may be hazardous if used improperly.

interrogate a thin transverse section through the body. The source and detectors rotate together around the patient producing a series of one-dimensional projections at a number of different angles. The projection data are mathematically reconstructed to create a 2-D image of a slice through the body. Digital geometric processing can be used to generate a three-dimensional (3-D) image of the inside of objects from a series of 2-D image slices taken around a single axis of rotation. Historically, images have been generated in the axial (transverse) plane that is orthogonal to the long axis of the body. Today's modern scanners can reformat the data in any orientation (orthogonal or oblique to the body axis) or as a volumetric representation.

Key Concept 1.3: Imaging Modalities

Modalities can be characterized by their energy source as invasive (using ionizing radiation) or non-invasive. They are acquired in 2-D planar projection mode or tomographic cross-section; and produce images representative of anatomical structure and/or physiological or molecular function.

- Medical modalities produce representations of **anatomical (structural) or molecular/physiological (functional)** information of the imaged body parts. For example, X-ray images are representations of the distribution of the linear attenuation coefficients of tissues and are largely images of anatomy or the structural nature of the tissues in the body. Radioisotope imaging of nuclear medicine produces images of the distribution of chemical, molecular, or physiological function of the tissue. Some modalities, such as ultrasound, can provide other types of functional measures, such as flow through vessels.

Key Concept 1.4: X-Ray Attenuation

Attenuation of an X-ray beam is largely a function of tissue radiodensity. Bone, for example, has a higher attenuation coefficient than soft tissue. In a radiograph of the chest, bony structures highly attenuate (or absorb) X-rays, passing less signal through the body to the detector; whereas soft tissues are less attenuating, passing more signal through to the detector. Air is least attenuating, and thus high signal hits the detector and is represented as black in most images; no signal hitting the detector is usually represented as white. In a chest radiograph, the air spaces in the lungs appear black, soft tissues are lighter gray, and the bony ribs and spine are white.

1.2 Diagnostic Imaging Modalities

For each diagnostic modality given below, the energy source and detector used in image formation are listed along with the tissue characteristic or attribute represented by the modality. Advantages and disadvantages for each are included.

1.2.1 Projection Radiography

**Further Reading 1.5:
Physics of Medical Imaging**

- Bushberg JT, Seibert JA, Leidholdt EM, Boone JM. *The Essential Physics of Medical Imaging*. Philadelphia, PA: Lippincott Williams & Wilkins; 2002.
- Huda W, Slone R. *Review of Radiologic Physics*. Philadelphia, PA: Lippincott Williams & Wilkins; 2003.
- Sprawls P. *Physical Principles of Medical Imaging*. New York, NY: Aspen Publishers, Inc.; 1993.

- Source: X-rays; ionizing radiation; part of the electromagnetic spectrum emitted as a result of bombardment of a tungsten anode by free electrons from a cathode.
- Analog detector: fluorescent screen and radiographic film.
- Digital detector: **computed radiography (CR)** uses a photostimulable or storage phosphor imaging plate; direct **digital radiography (DR)** devices convert X-ray energy to electron–hole pairs in an amorphous selenium photoconductor, which are read out by a thin-film transistor (TFT) array of amorphous silicon (Am-Si). For indirect DR devices, light is generated using an X-ray sensitive phosphor and converted to a proportional charge in a photodiode (e.g., cesium iodide scintillator) and read out by a charge-coupled device (CCD) or flat panel Am-Si TFT array.
- Image attributes: variations in the **grayscale** of the image represent the X-ray attenuation or density of tissues; bone absorbs large amounts of radiation allowing less signal to reach the detector, resulting in white or bright areas of the image; air has the least attenuation causing maximum signal to reach the detector, resulting in black or dark areas of the image.
- Advantages: fast and easy to perform; equipment is relatively inexpensive and widely available; low amounts of radiation; high spatial resolution capability. Particularly useful for assessing the parts of the body that have inherently high contrast resolution but require fine detail such as for imaging the chest or skeletal system.
- Disadvantages: poor differentiation of low contrast objects; superposition of structures makes image interpretation difficult; uses ionizing radiation.

**Thought Problem 1.6:
Radiation Dose**

Exposure to radiation at excessive doses can damage living tissue. Note however that the radiation exposure for a chest X-ray in the diagnostic range is equivalent to the amount of radiation exposure one experiences over a 10-day period from natural surroundings alone.

1.2.2 Fluorography

- Source: continuous low-power X-ray beam; ionizing radiation.
- Detector: X-ray image intensifier amplifies the output image.

- Image attributes: **continuous acquisition of a sequence of X-ray images** over time results in a real-time X-ray movie.
- May use inverted grayscale (white for air; black for bones).
- Advantages: Can image anatomic motion and provide real-time image feedback during procedures. Useful for monitoring and carrying out barium studies of the gastrointestinal tract, arteriography, and interventional procedures such as positioning catheters.
- Disadvantages: Lower quality moving projection radiograph.

1.2.3 Computed Tomography (CT)

- Source: collimated X-ray beam; X-ray tube rotates around the patient.
- Detector: early sensors were scintillation detectors with photomultiplier tubes excited by sodium iodide (NaI) crystals; modern detectors are solid-state scintillators coupled to photodiodes or are filled with low-pressure xenon gas. An image is obtained by computer processing of the digital readings of the detectors.
- Image attributes: thin transverse sections of the body are acquired representing an absorption pattern or X-ray attenuation of each tissue. Absorption values are expressed as **Hounsfield Units**.
- Advantages: **good contrast resolution** allowing differentiation of tissues with similar physical densities; **tomographic acquisition** eliminates the superposition of images of overlapping structures; advanced scanners can produce images that can be viewed in multiple planes or as volumes. Any region of the body can be scanned; has become diagnostic modality of choice for a large number of disease entities; useful for tumor staging.
- Disadvantages: high cost of equipment and procedure; high dose of ionizing radiation per examination; artifacts from high contrast objects in the body such as bone or devices.

Definition 1.7: Hounsfield Unit

CT number representing absorption values of tissues; expressed on a scale of + 1000 units for the maximum X-ray beam absorption of bone to –1000 units for the least absorbent air. Water is used as a reference material for determining CT numbers and is, by definition, equal to 0.

1.2.4 Magnetic Resonance Imaging (MRI)

- Source: **high-intensity magnetic field**; typically, helium-cooled superconducting magnets are used today; non-ionizing; gradient coils turn **radiofrequency (RF) pulses** on/off.

Key Concept 1.8: MRI Procedure

The patient is subjected to a magnetic field, which forces the H^+ nuclei to align with the magnetic field; an excitation pulse of radiofrequency is applied to the nuclei, which perturbs them from their position; when the pulse is removed, the nuclei return to their original state releasing energy, which can be measured and converted to a grayscale image.

- Detector: phased array receiver coils capable of acquiring multiple channels of data in parallel.
- Image attributes: produces images of the body by utilizing the magnetic properties of certain nuclei, predominately hydrogen (H^+) in water and fat molecules; the response of magnetized tissue when perturbed by an RF pulse varies between tissues and is different for pathological tissue as compared to normal.
- Advantages: **non-ionizing radiation**, originally called nuclear magnetic resonance (NMR) but because the word "nuclear" was associated with ionizing radiation, the name was changed to emphasize the modality's safety; can image in any plane; has excellent soft tissue contrast detail; visualizes blood vessels without contrast; no bony artifact since no signal from bone; particularly useful in **neurological, cardiovascular, musculoskeletal, and oncological imaging**.
- Disadvantages: high purchase and operating costs; lengthy scan time; more difficult for some patients to tolerate; poor images of lung fields; inability to show calcification; **contraindicated in patients with pacemakers or metallic foreign bodies**.

1.2.5 *Nuclear Medicine and Positron Emission Tomography (PET)*

Definition 1.9: SPECT

Single-Photon Emission Computed Tomography; a tomographic slice is reconstructed from photons emitted by the radioisotope in a nuclear medicine study.

- Source: X-ray or γ-ray emitting radioisotopes are injected, inhaled, or ingested; most common isotopes are technetium-99, thallium-201, and iodine-131.
- Detector: gamma camera with NaI scintillation crystal measures the radioactive decay of the active agent; emitted light is read by photomultiplier tubes; pulse arithmetic circuitry measures number and height of pulses. Further, these pulses are converted to electrical signal that is subsequently processed into a grayscale image.
- Image attributes: metabolic, chemical, or physiological interactions of the radioisotope are measured. The radioisotope chemical is distributed according to physiological function so the image primarily represents functional

information; however since function is distributed in the physical structures, recognizable anatomical images are produced.

- Advantages: **measures targeted specific chemical-physiologic tissue function**; valuable diagnostic tool particularly for imaging infarcts in the cardiovascular system, perfusion, and ventilation scanning of the respiratory tract for pulmonary embolus, imaging uptake at sites of increased bone turnover as in arthritis and tumors, assessing focal nodules, and in oncologic assessment.
- Disadvantages: high cost; PET isotopes require a cyclotron for production.

Definition 1.10: PET

Positron Emission Tomography uses cyclotron-produced positron-emitting isotopes including oxygen, carbon, nitrogen, and fluorine enabling accurate studies of blood flow and metabolism; positron isotopes are short-lived positively charged electrons; main clinical applications are in the brain, heart and tumors.

1.2.6 Ultrasound

- Source: high-frequency sound waves produced by a transducer made of a piezoelectric crystal.
- Detector: the **source transducer also functions as a receiver** of reflected sound and converts the signal into an electric current, which is subsequently processed into a grayscale image.
- Image attributes: sound waves travel through the body, are affected by the different types of tissues encountered and reflected back; a moving image is obtained as the transducer is passed across the body.
- Advantages: relatively **low cost**; non-ionizing energy source and **safe**; can scan in any plane; equipment is **portable** and can be used for bedside imaging; particularly useful for monitoring pregnancy, imaging the neonatal brain, visualizing the uterus, ovaries, liver, gallbladder, pancreas, and kidneys, confirming pleural effusions and masses, and assessing the thyroid, testes, and soft-tissue lesions.
- Disadvantages: **operator-dependent**; poor visualization of structures underlying bone or air; scattering of sound through fat yields poor images in obese patients.

Definition 1.11: Doppler Ultrasound

A technique to examine moving objects in the body. Blood flow velocities can be measured using the principle of a shift in reflected sound frequency produced by the moving objects. Can be used to image the cardiac chambers and valves of the heart, arterial flow, particularly to assess the carotids and peripheral vascular disease, and venous flow studies for the detection of deep-vein thrombosis.

1.2.7 Visible Light

- It is non-invasive but has limited ability to penetrate tissues deeply like the energies used in radiological imaging. Visible light imaging is used in light microscopy for pathological diagnosis, hematology, dermatology to photograph the skin, gastroenterology (colonoscopy/endoscopy), ophthalmology to image the retina, and during surgical procedures.

1.3 Digital Images

1.3.1 Definition

- A continuous image $f(x,y)$ is a 2-D light intensity function f at spatial coordinates x,y; the value f at location x,y is proportional to the brightness or grayscale of the image at that point.
- A **digital image** is an image $d(x,y)$ that has been **discretized (digitized)** both in space (physical location) and in amplitude (gray level); it can be considered as a matrix whose row and column indices identify a point x_1,y_1 in the image, and the corresponding matrix element value $d(x_1,y_1)$ identifies the gray level at that point. Elements in the digital array are called **pixels** for picture elements and each is represented by a numerical value in the computer. 3-D images consist of **voxels** or volume elements (Fig. 1.1).

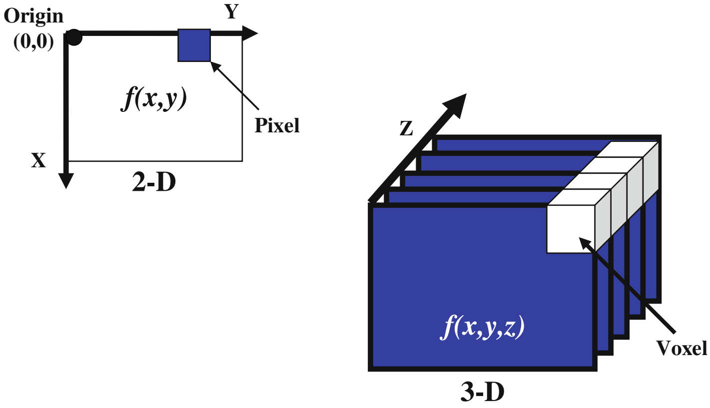

Fig. 1.1 Graphical representations of a pixel and a voxel.

1.3.2 Digital Image Formation

- To be suitable for computer processing, an image function must be digitized both spatially and in amplitude. Image **sampling** is the digitization of the spatial coordinates and is related to **pixel size,** reflective of matrix size and affects **spatial resolution**.

- Image gray level **quantization** is digitization of the amplitude or brightness, is determined by computer **bit depth,** and is reflected in the **image contrast resolution**.
- The process of digital image production includes **scanning** of the analog image line-by-line to obtain a continuous analog signal representing the variations in image brightness; followed by dividing the analog signal into individual pixels in a process known as **spatial sampling,** which is typically performed in equal intervals; this is followed by converting the amplitude into a digitized numerical pixel value in the process of **contrast quantization**; lastly, an **analog-to-digital (ADC) converter** turns the quantized level into binary code (Fig. 1.2).

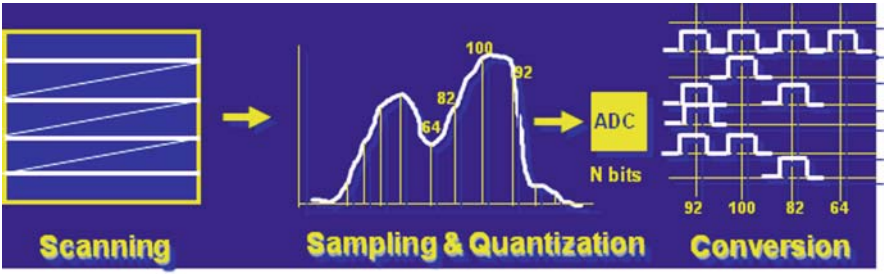

Fig. 1.2 The digital image formation process including scanning, sampling and quantization, and analog-to-digital conversion.

1.3.3 *Image Quality Factors*

- **Spatial resolution** limits sharpness (edges separating objects in the image) or visibility of fine detail and is a function of sampling that affects matrix and pixel size. Since each pixel can have only one numerical value, it is not possible to observe any anatomical detail within a pixel. More frequent sampling that results in smaller pixels (larger matrix sizes) provides better visibility of fine detail and a better quality higher spatial resolution image. If images are insufficiently sampled, the poorer resolution images may have a characteristic blockiness or checkerboard artifact.
- **Contrast resolution** limits differentiation of detail within and between objects and is a function of the bit depth used to represent the grayscale quantization. Insufficient quantization can result in false contouring or ridges in which smoothly varying regions of an object within the image become undifferentiable.
- **The total resolution of a digital image is the combination of the spatial resolution and the contrast resolution.** An image file size is equal to the product of

Key Concept 1.12: Image Quality

A tradeoff between spatial resolution and contrast or density resolution; an image with intrinsically poor spatial resolution can be made visually sharper by enhancing the contrast.

the matrix size (number of rows times number of columns) times the number of 8-bit bytes required to represent the image bit depth. For example, a CT slice is typically 512 rows by 512 columns and the grayscale is represented by 16 bits. It requires 2 bytes to account for 16 bits of grayscale, and therefore, a CT slice file size is then 512 × 512 × 2 = 524,288 bytes or approximately half a megabyte (MB). A single-view **chest radiograph** is approximately **10 MB**.

- **Noise** is a characteristic of all medical images; increased noise can lower image quality; noise is sometimes referred to as image mottle and gives the image a textured, snowy, or grainy appearance that can degrade visibility of small or low contrast objects. The source and amount of image noise depend on the imaging method; nuclear medicine images generally have the most noise, followed by MRI, CT, and ultrasound; radiography produces images with the least amount of noise.

Pearls 1.13

- Medical images have special features that make them difficult to create, acquire, manipulate, manage, and interpret. Complexities include human variability, performance requirements, safety considerations, motion artifacts, technical limitations, and cost.
- Diagnostic imaging modalities are categorized by their sources (ionizing or non-ionizing radiation), acquisition mode (projection or cross-section), and tissue property measured (anatomic structure or molecular function).
- Medical imaging hierarchy includes patient, examination (study), series (sequence), image, and pixel.
- Digital images are discretized (digitized) by sampling in space (location) and quantizing in contrast (grayscale).
- Spatial resolution limits sharpness or visibility of fine detail and edges in the image; it is a function of sampling that affects matrix and pixel size.
- Contrast resolution limits the number of different colors or grayscales represented in the image and is a function of quantization bit depth.

Suggested Reading

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Self-Assessment Questions

1. Which of the following is the most significant source of artifact in medical images?
   a. Human variability
   b. Patient positioning
   c. X-ray dose
   d. Subject motion
   e. Safety considerations

2. Which of the following imaging modalities use ionizing radiation as its source?
   a. Magnetic Resonance Imaging
   b. Computed Tomography
   c. Ultrasound imaging
   d. All of the above
   E. None of the above

3. Which of the following modality is most affected by the skill of the operator?
   a. Projection radiography
   b. Ultrasound
   c. Computed Tomography
   d. Magnetic Resonance Imaging
   e. Positron Emission Tomography

4. In the formation of a digital image, sampling affects which of the following?
   a. Visible fine detail
   b. Image matrix size
   c. Spatial resolution
   d. All of the above
   e. None of the above

5. Which imaging modality provides higher spatial resolution?
   a. Chest radiograph
   b. Chest CT

Chapter 2
Computers and Networking

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Contents

2.1 Introduction

The core infrastructure of any modern Radiology department is made up of computers/computer workstations and the connectivity or *networking* capability between these devices. All transactions between modalities, PACS, scheduling, billing, dictation, and reporting systems are made possible through specialized computer programs or *applications* that are executed by computers. Computer systems are quite diverse and are often designed to augment a specific task, whether it is to support image reconstruction for a modality such as computed tomography (CT) or digital radiography (DR) or rapid image display as in PACS. Fundamentally, all computers are built around a similar base design with enhancements in specific areas to address certain needs such as rapid storage access and data transfer for fileservers and improved video characteristics for PACS client display stations. The purpose of this chapter is to familiarize the reader with the fundamentals of computer architecture, networking, and computer applications.

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2.2 Computers 101 – Hardware

2.2.1 Hardware Elements of Computers

- There are five **core hardware components** of the modern digital computer system: the central processing unit or **CPU, memory, input devices, output devices, and a bus**. While some components are given greater emphasis for a particular computer design (e.g., a faster CPU for computationally intensive tasks), virtually all types of computers have these five key components represented. Most of the hardware components in the modern digital computer are contained within small modular semiconductor packages (**integrated circuits [ICs] or chip**) that, in turn, contain millions of discrete components. Numerous ICs are interconnected on a large circuit board, frequently referred to as the **motherboard.** The motherboard is interfaced with other outside components (e.g., disk drives, power supply, keyboard, network, etc.) using specialized couplers that provide necessary power and connectivity to **peripheral devices** such as disk drives (storage), video displays, and keyboards.

Key Concept 2.1:
Core Computer Hardware Components

- CPU
- Memory
- Input devices
- Output devices
- Bus

- The **central processing unit** (**CPU**) or **microprocessor** is typically the largest integrated circuit on the motherboard and its role is to execute specific commands or **instructions/machine code** dictated by a computer program and orchestrate the movement of data and instructions through the entire computer system. Although the CPU is frequently personified as the "brain" of the computer, it has no innate "intelligence" or inherent ability to make decisions. The CPU's strength is in its ability to process instructions and manipulate data at amazing speeds. In this regard, it is the perfect soldier; it follows all commands presented to it with blazing efficiency.
- The number of instructions that a CPU can perform per second is expressed as its **clock speed**. Typical personal computer CPUs can perform over 3 billion instructions per second or 3 gigahertz (3 GHz). Modern CPUs actually contain two to eight CPUs in one IC or chip (**multi-core CPU**). This provides unparalleled computational speed as each core shares the processing tasks formerly assigned to one CPU. While the strength of the CPU is in its ability to process instructions, it has limited capability to store data before or after execution. The CPU relies on physical memory to store this information and provides it to the CPU on demand.

- **Memory** is principally used to temporarily store data (and results) and applications or programs. In contrast to the CPU, a memory module has no capability to process instructions; instead memory is designed to reliably store large chunks of data and then release these data on command (often at the behest of the CPU). Physical memory can exist in **solid-state** form as an IC or as **physical media** (spinning disk, compact disk [CD], or digital versatile disk [DVD]). A solid-state memory module that can be erased and rewritten for unlimited number of times is generically referred to as **random access memory or RAM.**
- Memory that can only retain data with power applied is referred to a **volatile memory** – most of the motherboard memory modules are of this type. These are rated by their **storage capacity** (given in megabytes or gigabytes), **access speed** (in nanoseconds), **data rate** (DDR2), and **configuration** (single or dual inline memory SIMM or DIMM).
- **Non-volatile memory** will retain data written to it until it is erased or overwritten. Examples include USB memory sticks and disk drives. Since the inherent speed of non-volatile memory is substantially slower than that of volatile memory, volatile RAM is typically employed on the motherboard to augment data processing.
- Some forms of memory are designed for specific tasks. **Video memory (VRAM)** is employed on video graphics cards to store graphical information to improve video display performance. A specialized form of high-performance memory is found on most CPUs to help efficiently buffer data that move in and out of the microprocessor core (**L2 cache memory**).
- There are additional forms of computer memory that are classified simply as **storage**, principally because they are characterized by slower speed compared to solid-state memory and non-volatile characteristics (data persist indefinitely until erased/overwritten). These are made up of spinning media (disk drives, CDs, and DVDs) and linear media (tape).
- **On-line storage** refers to high-performance, non-removable media that requires no human or mechanical intervention to retrieve. Data on spinning hard disk arrays are an example of on-line storage. **Near-line storage** consists of removable media (e.g., tapes, CDs, or DVDs) that are made available through mechanical means such as a robotic tape or optical disk jukebox. The efficiency of data retrieval with a near-line system is dependant upon the mechanical speed of the robotic system and the queuing mechanism of the media. **Off-line storage** is removable media that requires human intervention to load and retrieve data. As a result, performance

Key Concept 2.2:
Types of Data Storage

- On-line
- Near-line
- Off-line

is the lowest for off-line storage. While off-line storage is the least expensive storage strategy, it is otherwise quite inefficient and is therefore reserved for data that have a low probability for future use.

- **Input/output devices** are hardware extensions that allow humans (or other devices) to interact with a computer. Examples of input devices include the keyboard, touch screen, mouse, microphone, and camera. Typical output devices include the video display, printer, plotter, and speaker.
- Because the typical microprocessor can execute several billions of commands per second, it is highly dependant upon an efficient mechanism for delivering instructions and data to it. This requires that there is a well-orchestrated method for moving data between the motherboard components and the CPU. The **data bus** is the physical data chain built into the motherboard that allows for this efficient data transfer. This is supported by several ICs, known as the **chipset**, which coordinates uninterrupted data transfers through the bus. Multiple different designs have been developed; the most common in use today is peripheral component interconnect (PCI) and PCI-Express. The data bus is defined by a **data-width** (typically 32 or 64 bits), which specifies how much data are delivered across the bus per cycle and a **clock speed** (given in megahertz).
- Another key component to the typical computer motherboard is the **basic input/output system (BIOS)**. The BIOS is comprised of a non-erasable read only memory (ROM) chip that contains the minimal amount of software necessary to instruct the computer how to access the keyboard, mouse, display, disk drives, and communications ports.

Key Concept 2.3: Booting Up

The motherboard, the CPU, and memory retain no previous information about how the computer is configured. Every time the computer turns on, it pulls itself up by its bootstraps ("booting up").

- When the power is first applied to the computer, the motherboard relies on the BIOS to tell what additional components are available to the motherboard for input and output (e.g., disk drives, memory, keyboard, etc.). The motherboard "becomes aware" of what is available and how to access it, each and every time the computer is restarted.
- The BIOS also provides information to the motherboard on where to find the first piece of software to load during the startup process. The startup process is also known as the **boot process.** The first piece of software to load is usually a portion of the **operating system** that will coordinate the other software programs.

2.3 Computers 101 – Software

- Hardware can be seen and handled. Software, on the other hand, is a virtual concept. While we can handle the media that software is written on, we cannot actually "see" the software.
- The term "software" applies both to application programs and data.
- Software at its lowest level (the level at which it interacts with the CPU) consists of a long series of **bits** (ones and zeros). All data written to physical media, whether it is magnetic disk, USB stick, CD, DVD, or RAM memory is stored as an orderly series of bits. Eight-bit clusters of data form a **byte** of data.

Key Concept 2.4:
Software Versus Hardware

The fundamental distinction between software and hardware is that hardware exists as the tangible physical components and connections inside a computer.

- Software is divided into **system software** (or operating system) and **application software** – programs that help users to perform specific tasks and **programming software** (or development software) – programs that aid in the writing (i.e., coding) of other software.
- All software consists of individual procedures that command the computer to follow a precisely orchestrated series of instructions. The number of individual instructions specified in any one program varies depending upon the type and complexity of the software – from 10 to 100 million lines of code. (The Windows XP operating system, for example, contains approximately 40 million lines of code.)

Further Reading 2.5:
Core Computer Components

- White R, Downs TE. *How Computers Work*. 9th ed. Indianapolis, IN: Que Publishing; 2008.

- All computer software must be moved into storage (i.e., disk drive) or physical memory (RAM) before it can be **executed** by the microprocessor. The instructions are passed through a series of software layers where they ultimately reach the microprocessor. Each instruction causes the computer to perform one or more operations.

2.3.1 Computer Operating System

- The **operating system (OS)** is the underlying software that integrates the hardware with software applications. It is distinguished from the essential hardware components in that it consists entirely of *software* – millions of lines of machine commands that are understood and obeyed by the microprocessor. The OS actually consists of hundreds or thousands of individual programs that bundled together. Many of these individual programs are