CT for Technologists

4713-202

MSK and Spine CT

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This material will be reviewed for continued accuracy and relevance.

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The skill of the technologist is the single most important factor in obtaining high quality diagnostic images. A successful CT examination is the culmination of many factors under the direct control of the technologist.

CT for Technologists is a training program designed to meet the needs of radiologic technologists entering or working in the field of computed tomography (CT). This series is designed to augment classroom instruction and on-site training for radiologic technology students and professionals planning to take the review board examinations, as well as provide a review for those looking to refresh their knowledge base in CT imaging.

CT for Technologists・MSK and Spine CT prepares the learner to safely and effectively acquire diagnostic CT images of the musculoskeletal system and spine. Careful patient screening and preparation are essential for ensuring a quality exam. A working knowledge of skeletal and spinal anatomy is key to correctly position the patient to acquire diagnostic images. After a review of the anatomy, the learner will be instructed on image acquisition by referencing multiplanar reconstructions for each region of interest.

EDUCATIONAL CREDIT

This program has been approved by the American Society of Radiologic Technologists (ASRT) for 2.25 hours of ARRT Category A continuing education credit.

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OBJECTIVES

After completing this material, the learner should be able to:

- Prepare and appropriately screen and evaluate the patient for a CT scan of the musculoskeletal system or spine
- Identify correct positioning methods when performing a musculoskeletal or spinal CT scan
- Appropriately prepare and administer iodinated contrast when a contrast-enhanced CT exam is indicated
- Identify the important anatomic structures of the upper and lower extremities
- Describe the primary indications for CT scanning of the joints, pelvis, and sternum
- Incorporate the latest technologic advances in CT imaging to scanning protocols of the musculoskeletal system
- Identify the important anatomic landmarks of the cervical, thoracic, lumbar, and sacral spine
- Describe the primary indications for CT scanning of the cervical, thoracic, lumbar, and sacral spine
- Apply appropriate protocols for optimized CT imaging of the spine

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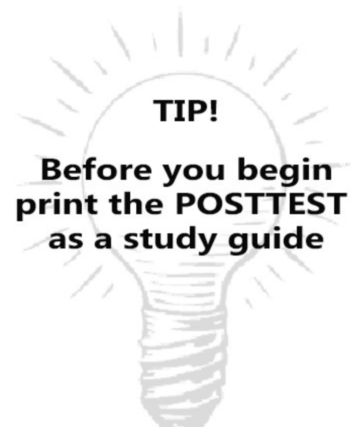

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Please note: tuition payments are **non-refundable**.

FACULTY BIOGRAPHY

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In addition to managing the 3D Lab at Fairfax Radiological Consultants (FRC), Mr. Jennings oversees CT protocols at six outpatient CT centers and has served as Director/Instructor of the GE/FRC *Cardiac CTA for CT Technologists* course.

Mr. Jennings has authored two online educational units from the *CT for Technologists* series - *Radiation Safety* and *Screening with CT* - in collaboration with ICPME.

Additionally, Mr. Jennings served as co-author with James P. Earls, MD, on a 2008 publication in *Radiology* titled: *Prospectively gated transverse coronary CT angiography versus retrospectively gated helical technique: improved image quality and reduced radiation dose.*

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ACKNOWLEDGMENTS

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Additionally, we would like to thank the faculty who contributed to the original content, released in 2005: Tomi Brandt, MPS, RT(R)(M)(QM); Bernard Assadourian, BA, RT(R)(CT); and Alec J. Megibow, MD, MPH, FACR.

DISCLAIMER

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CHAPTER ONE

An Overview of the CT Examination

After completing this section, the learner will be able to:

- Prepare and appropriately screen and evaluate the patient for a CT scan of the musculoskeletal system or spine
- Identify correct positioning methods when performing a musculoskeletal or spinal CT scan
- Appropriately prepare and administer iodinated contrast when a contrast-enhanced CT exam is indicated

INTRODUCTION

Plain X-ray and magnetic resonance imaging (MRI) are widely used in the evaluation of musculoskeletal (MSK) conditions and diseases. However, with the advent of multidetector CT scanners and 3D imaging, there has been renewed interest and utility in CT scanning for the musculoskeletal system and spine.

In order for the technologist to properly perform musculoskeletal CT examinations, full appreciation of the following is necessary:

- pretest preparation; ensuring all necessary examinations have been performed or scheduled
- presentation of the patient to the CT department, which includes accurate documentation of all prior surgical procedures
- proper screening of the patient
- physically preparing the patient for the CT scan
- instructing the patient about what to expect from the CT examination
- appropriate use of contrast agents in consultation with the radiologist
- proper positioning of the patient on the CT table
- understanding any specific positioning to best study the appropriate region of interest

Carefully following these steps will help the technologist obtain a high-quality scan, avoid the need for repeat scans, and reduce both the patient's anxiety and exposure to unnecessary radiation.

PATIENT SCREENING

Following proper identification of the patient through the medical record and ID bracelet (depending on the departmental or facility practice), a thorough interview to assess the patient's history should be conducted. The time spent on history-taking has several goals:

- To assess the safety of the procedure based on the patient's history. In particular, specific information about the presence of risk factors for intravenous (IV) contrast administration must be obtained, including any history of a reaction to iodinated intravenous contrast agent.
- To verify that the information in the patient's chart is accurate and that the patient has been scheduled for the correct examination.
- To assess the patient's level of comprehension about the exam.
- To establish initial rapport with the patient and ease anxiety about the examination.

IV contrast is used for very specific clinical indications; however, because most musculoskeletal exams do not require IV contrast, contrast should be used only on the recommendation of a radiologist. Safe administration of IV contrast is determined by assessing potential risk factors. Any history of renal disease, heart failure, or insulin-dependent Type 1 diabetes should be documented; these conditions may preclude the use of an IV contrast agent or require that special precautions be taken or routine protocols be modified.

eGFR

Before injecting contrast, an estimated glomerular filtration rate – eGFR – should be calculated to determine if the patient's kidneys are functioning well enough to receive iodinated contrast. eGFR is calculated using a blood test to measure serum creatinine, which measures kidney function, in combination with the patient's age, gender, and race. An eGFR lower than 60 is considered abnormal and may result in a lower contrast volume or preclude the use of contrast altogether. The decision to use contrast with an abnormal eGFR should be made by the radiologist or by a pre-determined policy of the radiology practice or hospital.

The American College of Radiology (ACR) provides indications for renal assessment before the administration of IV iodinated contrast:

- Age > 60
- History of renal disease, including:
  - Dialysis
  - Kidney transplant
  - Single kidney
  - Renal cancer
  - Renal surgery
  - History of hypertension requiring medical therapy
  - History of diabetes mellitus
  - Metformin or metformin-containing drug combinations*

* Metformin does not confer an increased risk of contrast-induced nephropathy. However, patients who develop acute kidney injury (AKI) while taking metformin may be susceptible to the development of lactic acidosis.

Patients who are scheduled for a routine intravascular study but do not have one of the above risk factors do not require a baseline serum creatinine determination before iodinated contrast medium administration. However, be sure to refer to your department's protocol for obtaining pre-CT testing.

For additional information, the *ACR Manual on Contrast Media, Version 10.3*, *2018*, can be found at: https://www.acr.org/-/media/ACR/Files/Clinical-Resources/Contrast_Media.pdf

eGFR calculators can be found online; this link to the National Institute of Diabetes and Digestive and Kidney Diseases provides calculators for both adult and pediatric patients: https://www.niddk.nih.gov/health-information/communication-programs/nkdep/laboratory-evaluation/glomerular-filtration-rate-calculators

Metformin

Metformin is a medication used primarily for patients who have non-insulin dependent diabetes mellitus, usually Type II diabetes. Past recommendations of abstaining from taking metformin for all patients 24 hours prior and 48 hours after receiving any type of IV contrast have been recently modified by the American College of Radiology. Currently, only patients with an eGFR < 30 need to discontinue use of metformin for 48 hours after the procedure.

After the subsequent 48 hours, it is recommended that the patient's kidney function be re-evaluated to determine if metformin can again be safely used. Please note that it is rare to administer IV contrast in a patient with an eGFR <30, so most patients who take metformin will likely not undergo a contrast-enhanced CT exam.

For patients with no evidence of AKI and eGFR ≥30, there is no need to discontinue metformin either before or following the IV administration of iodinated contrast material, nor is there a need to reassess the patient's renal function following the test.

For additional information, the *ACR Manual on Contrast Media, Version 10.3*, *2018*, can be found at: https://www.acr.org/-/media/ACR/Files/Clinical-Resources/Contrast_Media.pdf

History of Allergic/Allergic-like Reaction to Iodinated Contrast

Determining if there is a history of a true allergic reaction is essential for any patient potentially receiving IV contrast of any type. If the patient recalls a possible reaction to a contrast medium, the reaction should be explored fully, using the questions in **Table 1** to guide the discussion.

Table 1. Patient screening questions regarding previous contrast reaction. Adapted from Adler AM, Carlton RR. Introduction to Radiography in Patient Care. 2nd ed. Philadelphia, Pennsylvania; W.B. Saunders Company; 1999.

When and where did the contrast reaction occur?
What was the nature of the reaction (a systemic reaction or a reaction localized to the injection site)?
Do you know which contrast agent was used (ionic vs nonionic agent, or barium)?
What were the symptoms?
Did the reaction require ANY treatment?
How were the symptoms treated (With epinephrine? With diphenhydramine? By injection or oral medication?)
If you were not already a hospital patient, were you hospitalized for the contrast reaction?
Have you undergone CT examination with contrast administration since the reaction occurred?

If there is the potential for a contrast reaction that is not already noted in the chart, the technologist should document the information for future reference. Patients with a history of a contrast reaction may require a steroid premedication regimen prior to the injection of IV contrast. The American College of Radiology recommends that patients with a history of adverse contrast reactions be premedicated prior to IV contrast administration as follows:

- 50mg prednisone administered 13 hours, 7 hours, and 1 hour prior *and*
- 50mg diphenhydramine (Benadryl®) intravenously, intramuscularly, or by mouth 1 hour prior

An alternate premedication regimen requires 32mg methylprednisone 12 hours and 2 hours prior to the administration of contrast with the option of administering 50mg of diphenhydramine 1 hour before, as noted above. Because diphenhydramine can cause drowsiness, it is recommended that the patient arrange for transportation to and from their CT exam.

Past Medical History/Surgery

History-taking should also include questions about current medical conditions, previous medical illnesses, radiation therapy and, most important of all, prior surgery. This information can help minimize errors of interpretation in cases where there has been extensive postsurgical scarring (which may be misinterpreted as disc herniation) or where the musculoskeletal anatomy has been altered, such as in cases of joint repair or replacement. The patient should be asked about the approximate dates of any prior imaging examinations; interpretive errors are also minimized when previous images are available for comparison.

It is important to ensure that the patient understands the purpose of the exam and is able to follow instructions given by the technologist. A family member or interpreter may be necessary during the screening process especially if the patient does not speak English or has diminished mental status. It is important to keep in mind that patients who present for CT scans may have concomitant medical conditions that affect cognitive functioning; for example, trauma patients may be unable to provide any history at all.

Pregnant Patients

Elective CT studies are contraindicated for pregnant patients. The possibility of pregnancy is of particular concern in, for example, lumbar spine or sacral CT where there is direct radiation exposure to the pelvis, since the fetus is located directly within the region of interest and cannot be shielded from radiation. All women of childbearing age should be queried about the time of their last menstrual cycle; if there is any question about the possibility of pregnancy, an immediate urine pregnancy test can be given, or elective procedures can be rescheduled for a time during or immediately following the woman's menstrual cycle or after the end of pregnancy, if the patient is in fact pregnant. In emergency situations, such as diagnosing cervical spine trauma, which may affect the spinal cord and/or nerve roots, or pelvic fractures, the benefits of the examination may outweigh the risk of radiation exposure to the fetus, and the study may be performed. The physician responsible for ordering the examination should specifically document in the pregnant patient's medical record that she understands the risks and benefits of the CT scan, as well as alternative procedures available for her specific diagnosis, if any. Some facilities may require the patient sign a consent form or waiver, confirming that the patient is aware of and understands potential risks to the fetus before proceeding with the exam.

REDUCING RADIATION DOSE:
ITERATIVE RECONSTRUCTION and ALARA

Most spine and MSK CT exams are performed without the use of IV contrast, so the biggest risk to the patient is usually potential adverse radiation effects. Fortunately, CT scan manufacturers are using iterative reconstruction (IR) to lower radiation dose to the patient. In fact, IR has been shown to decrease radiation exposure to the patient by 50% or more. Dose reduction is achieved by lowering parameters such as mA, rotation time, and kVp, or by increasing pitch then applying IR algorithms to decrease image noise. These parameter changes result in decreased radiation dose to the patient while maintaining good image quality. Using IR properly is a balance between dose reduction and image quality. Applying too much IR can result in an image that is overly smooth, so it is vital that the technologist and radiologist work in tandem to identify the proper scan parameters and IR application that will produce good image quality for each protocol.

As for all imaging exams that require radiation exposure, the ALARA – as low as reasonably achievable – concept must be followed. The American College of Radiology "urges providers to use the minimum level of radiation needed in imaging exams to achieve the necessary results." The *Image Gently* and *Image Wisely* campaigns are ACR dose-reduction initiatives for pediatric and adult patients, respectively. For more information on the ACR Statement on FDA Radiation Reduction Program, click here:

https://www.acr.org/Advocacy-and-Economics/ACR-Position-Statements/FDA-Radiation-Reduction-Program

PREPARING THE PATIENT FOR THE PROCEDURE

The technologist must ensure that the patient knows what to expect before, during, and following the actual scan. Issues specific to CT scanning of the musculoskeletal system include the length of the procedure, specific patient positioning, and the use of contrast agents. Postsurgical or acutely injured patients may be experiencing pain, making it difficult to obtain ideal positioning. The technologist should always formulate a plan for adequately positioning the patient based on their current condition. Fortunately, the increased spatial resolution of modern scanners ensures that good quality reformatted images in the desired plane(s) can be acquired even when the patient's positioning is not optimal. Therefore, positioning should be a balance between the patient's comfort level and the optimal position.

Scan Length and Breath Holding

The length of the CT scan will vary according to the technology employed, eg, single-slice scanner vs multidetector-row scanner, the length of the region to be scanned, and the number of scans required.

Use of state-of-the-art CT technology has significantly decreased examination times. Combined with advances in postprocessing techniques, images are acquired almost instantaneously and can then be displayed in almost any viewing plane without loss of spatial resolution. Many examinations which might previously have required separate acquisitions can now be performed in a single scan, and these data can be used to rapidly create multiple views. Additionally, the actual rotation time combined with multidetector-row geometry significantly reduces the time the patient is actually in the scanner. The ability to acquire many thin slices within a short scan time over a longer *z*-axis coverage allows more precise delineation of the anatomic structures in question, as well as the surrounding tissues. The improvement in image quality and display are the direct result of the acquisition of data sets composed of very near isotropic voxels, as well as shortened scan times that minimize motion artifacts.

The patient should be instructed on breath holding prior to the procedure. It is important that the patient knows how long and how often they will be asked to hold their breath. With proper instruction, the technologist can successfully obtain crisp images with virtually no patient motion.

CURRENT CT TECHNOLOGY

Since the introduction of the first CT scanners more than four decades ago, technology has evolved with remarkable rapidity. From the first prototype scanners, which required about five minutes to acquire a single slice and an additional five minutes to reconstruct a single image, current multidetector-row CT scanners can scan the entire chest, abdomen, and pelvis in just seconds, acquiring slices of ≤ 1mm thickness.

Advances in CT image acquisition and quality can be attributed to the advent of helical (spiral) and multidetector-row CT scanners. Spiral CT was made possible through the introduction of slip-ring technology, which revolutionized CT scanning by allowing for continuous rotation of the tube and detectors (unlike older machines, in which the tube turned 360°, stopped, and reversed its direction). Multidetector-row machines have dramatically reduced image acquisition time while increasing resolution by allowing simultaneous acquisition of first two, then four, eight, 64, 128, 256 and now even 320 scans in a single rotation.

Although much of the imaging of the musculoskeletal system is performed using MRI, the widespread availability of multidetector-row CT has increased its application in musculoskeletal imaging. CT imaging is most useful for imaging bone, while cartilage and ligamentous abnormalities are better visualized with MRI. The increased applications of CT in musculoskeletal imaging have created a new set of challenges for technologists, including the need to pay greater attention to patient positioning and to consider alternative positioning to obtain quality scans in patients who cannot assume routine positioning.

Figure 1. Patient in the supine position, with arms above the head.
Available at: commons.wikimedia.org

PATIENT POSITIONING

Many musculoskeletal and spinal scans are performed with the patient placed feet first into the scanner. In most cases, the patient is scanned in the supine position. Depending upon the anatomy being scanned, the prone position or decubitus position (patient lying on their side) may be used instead. The arms should be raised above the head to avoid artifact noise (**Figure 1**).

For a scan of the thoracic spine, lumbar spine, or pelvis, patients are generally positioned feet first in the supine position with the arms placed above the head; for a cervical spine scan they are generally positioned head first in the supine position with the arms at the side. The feet first supine position is used in the following specific circumstances:

- when IV contrast is administered
- with patients who are claustrophobic
- for patients who have difficulty breathing and require head elevation
- for trauma patients in whom the extent of injury is not known

If the patient cannot raise both arms above the head, one arm should be raised, if possible. By optimizing the display field of view (DFOV) to include only the area of interest, the artifact caused by arms at the sides should be minimal.

Immobilization may be necessary for certain patients who are unable or unwilling to remain still for the duration of the procedure (**Table 2**). It is important to emphasize that immobilization devices are used to ensure the least amount of patient motion to achieve high-quality images. Trauma patients who enter the CT department with immobilization devices, such as restraint boards or neck braces, should be kept in these devices. With current multidetector-row CT scanners, the examination times are so fast that excellent studies can be obtained even with patients unable to cooperate.

Table 2. Patients who may require immobilization devices.

Young patients who are unable to stay still
Elderly patients who may be prone to tremor or other involuntary movements
Trauma patients who may be unable to remain still due to pain
Patients who are unlikely to remain still due to extreme anxiety over the procedure
Patients with loss of consciousness/altered mental status, for whom it may be impossible to explain the need for immobility
Patients who must be scanned in awkward positions (such as the decubitus position)
Patients requiring intravenous contrast administration with restraint of the arm on a board perpendicular to the body

Patient anxiety arises from normal fears concerning the results of the study, but also from the unknown components of the procedure itself. It is important to inquire directly about any areas of concern or embarrassment, making sure to explain the realities of the procedure if the patient's fears or beliefs about the procedure are inaccurate.

USE OF CONTRAST MEDIA

Contrast media are used in musculoskeletal and spinal CT scans to enhance the visibility of tissues and structures. Intravenous contrast media are used to enhance the blood vessels and help differentiate normal from abnormal tissue. CT myelography and CT arthrography require injection of contrast media within the spinal canal (myelography) or the joint space (arthrography). However, the widespread use of MRI has almost eliminated these two CT procedures.

Intravenous Contrast

The use, dose, volume, rate, and timing of intravenous contrast administration are critical factors in yielding high-quality, diagnostic CT scans in which the appropriate region of interest is optimally highlighted. Much of the scope of work of the CT team, including that of the technologist, centers around timing the delivery of IV contrast.

Most patients scheduled for an MSK or spinal CT scan usually will not receive IV contrast, except in a few specific cases. In the event that contrast is to be given, patients should be advised not to eat or drink anything for at least two hours prior to the administration of IV contrast to ensure that the stomach is empty. Patients should also be advised to hydrate well *prior* to the two-hour window of no food or drink in preparation for the exam. Hydration will aid kidney function as well as help with accessing the vein for IV injection.

The dose of IV contrast used varies significantly, depending on the patient's age, weight, cardiovascular health, and the area being imaged. The typical dose ranges from 75-150mL of low-osmolar nonionic (LOCM) iodinated contrast (300-370mgI/mL), injected at a rate of 2-3mL per second. Depending on the type of scanner used, initiation of imaging is either performed following a prescribed delay or after total administration of contrast, depending on the radiologist's order. When determining the proper mAs, factors such as scanner type, patient size, and scanning in axial or helical mode should be considered to ensure high-quality imaging.

Figure 2. 3D volume-rendered image of the hip.

All members of the healthcare team involved in the care of patients undergoing CT scanning should be thoroughly aware of the patient risks associated with IV contrast administration. Adverse reactions include allergic reactions (ranging from urticaria to anaphylactic shock); headache; injection site reactions, including extravasation into the tissue surrounding the injection site; anxiety; a feeling of warmth, flushing, and an urge to urinate; nausea; and a general feeling of discomfort. Although LOCMs carry a lower risk of adverse events compared with high-osmolar agents (HOCMs), adverse events may nevertheless occur with LOCM. Patients who have a previously confirmed or have experienced a possible reaction to a contrast agent should be further evaluated using the questions in **Table 1**.

Technological advances in multidetector-row CT scanners require continuous modifications in the rate and timing of IV contrast administration. Technologists must balance multiple factors in contrast administration, including injection site, injection rate, injection duration, bolus shaping, and scan timing, in order to provide the best possible enhancement and/or longest possible uniform duration of contrast. For the upper extremities, the technologist should be certain to administer the contrast in the arm *not* being imaged, as the contrast bolus can cause streak artifact if administered in the limb being studied.

SUMMARY

There are a number of important considerations specific to CT scanning of the musculoskeletal system and spine that technologists must familiarize themselves with to ensure the best possible scan results. As with other types of CT scans, procedures should be reviewed in detail with the patient, and patients should understand the specific role they play in ensuring a successful scan, including breath holding. Advances in technology have dramatically reduced CT scanning times, allowing generation of images with unparalleled resolution (**Figure 2**). These advances, however, have presented certain challenges to the technologist that must be met, including an increased level of expertise in the timing and delivery of contrast agents to correlate with image acquisition.

C H A P T E R T W O

CT Examination of the Musculoskeletal System

After completing this section, the reader will be able to:

- Identify the important anatomic structures of the upper and lower extremities
- Describe the primary indications for CT scanning of the joints, pelvis, and sternum
- Incorporate the latest technologic advances in CT imaging to scanning protocols of the musculoskeletal system

INTRODUCTION

This chapter will review the clinical indications, protocol development, and multiplanar reconstructions (MPR, also called *reformatting*) for CT imaging of the major joints—the shoulder, elbow, wrist, hip, knee, and ankle—as well for the pelvis and sternum.

The CT technologist must readily recognize the important bony landmarks that define clinical regions of interest for each of the major joints in the body. Familiarity with these landmarks will ensure the technologist includes the entire region of interest is included in the scan.

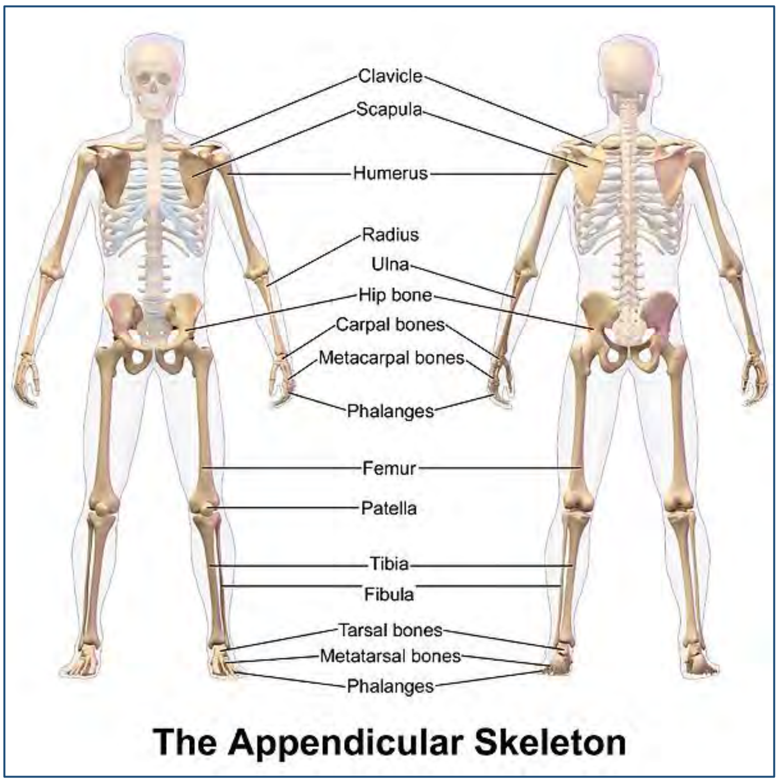

Figure 3. Illustration of the appendicular skeleton. Available at commons.wikimedia.org

UPPER EXTREMITY JOINTS

The appendicular skeleton is the portion of the skeleton that supports the appendages and includes the pectoral girdle, the pelvic girdle, and the limb bones (**Figure 3**). Anatomic details of each portion of the upper and lower extremities follow.

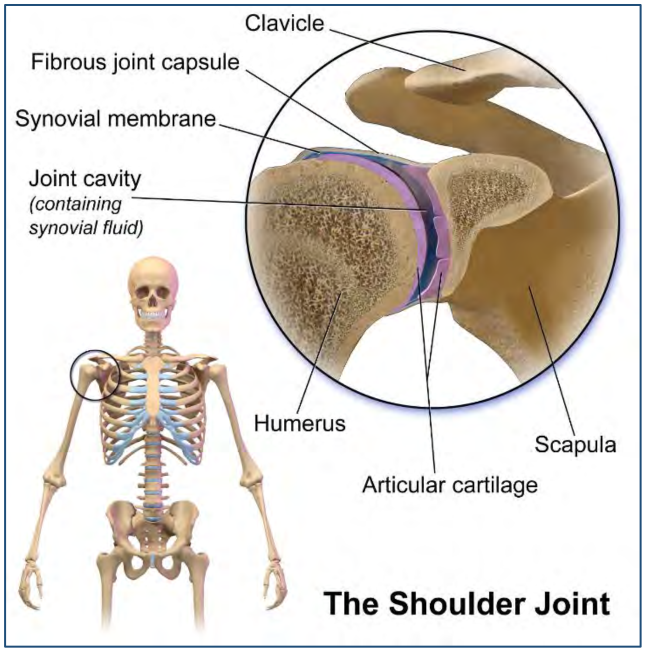

Figure 4. The shoulder joint. Available at wikipedia.org

The Shoulder: Clavicle, Scapula, and Humeral Head

The shoulder is a shallow ball-and-socket joint formed by the clavicle, the scapula, and the head of the humerus (**Figure 4**). These bones are supported by the rotator cuff and are cushioned by bursae, the sacs of synovial fluid that lubricate the joints. The clavicle is a long, slender bone that extends transversely from the sternum at the sternoclavicular joint to the acromion (part of the scapula), where it terminates at the acromioclavicular joint.

The scapula is a triangular-shaped flat bone that forms the posterior portion of the shoulder girdle (**Figure 5**). Four bony projections from the scapula provide sites of attachment for the muscles and ligaments of the shoulder. These projections are:

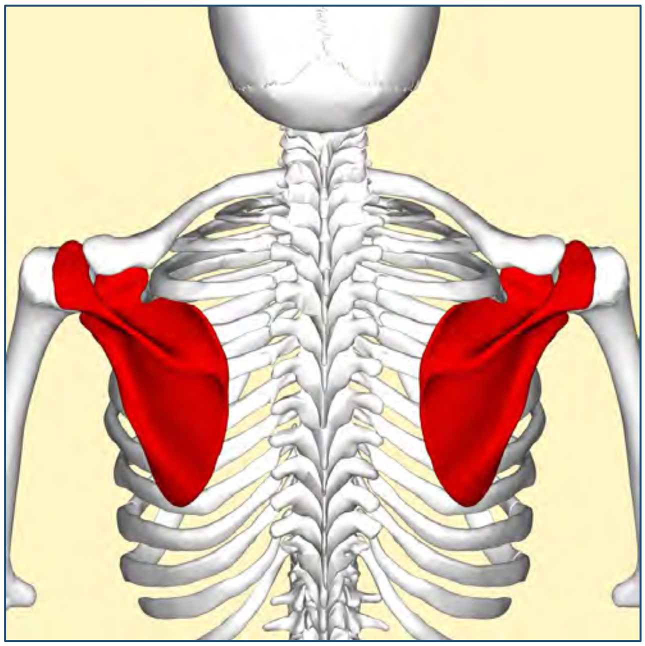

Figure 5. Posterior view of the scapula. Available at commons.wikimedia.org

- *acromion:* a flat process extending from the scapular spine that forms the highest point of the shoulder
- *scapular spine:* a projection arising from the upper third of the posterior surface of the scapula and extending obliquely to form the acromion
- *coracoid process:* a beak-like process located on the anterolateral surface of the scapula
- *glenoid process:* the largest bony projection of the scapula is actually a depression that cups the head of the humerus, creating a freely moving joint

The humeral head is comprised of two tubercles that provide attachment sites for muscle, tendons, and ligaments. The lesser tubercle arises along the anterior surface of the humeral head, with the greater tubercle arising from the lateral surface. These two tubercles are separated by the bicipital groove.

The muscles, tendons, and ligaments of the shoulder provide stability for the joint and are responsible for upper arm movement. The deltoid muscle—the shoulder cap—is primarily responsible for abduction of the arm (raising the arm away from the side); this muscle originates on the clavicle and acromion and blankets the shoulder joint. The rotator cuff is a musculotendinous structure that provides dynamic stability to the shoulder joint, allowing for abduction and rotation of the humerus (moving the arm from back to front). It is comprised of four muscles that surround the shoulder joint:

- *supraspinatus:* responsible for abduction of the arm
- *infraspinatus:* responsible for outward rotation of the arm
- *teres minor:* also rotates the arm outward
- *subscapularis:* responsible for medial rotation of the arm; it is the only muscle of the rotator cuff on the anterior surface of the scapula. The remaining muscles are located on the posterior surface (**Figure 6**).

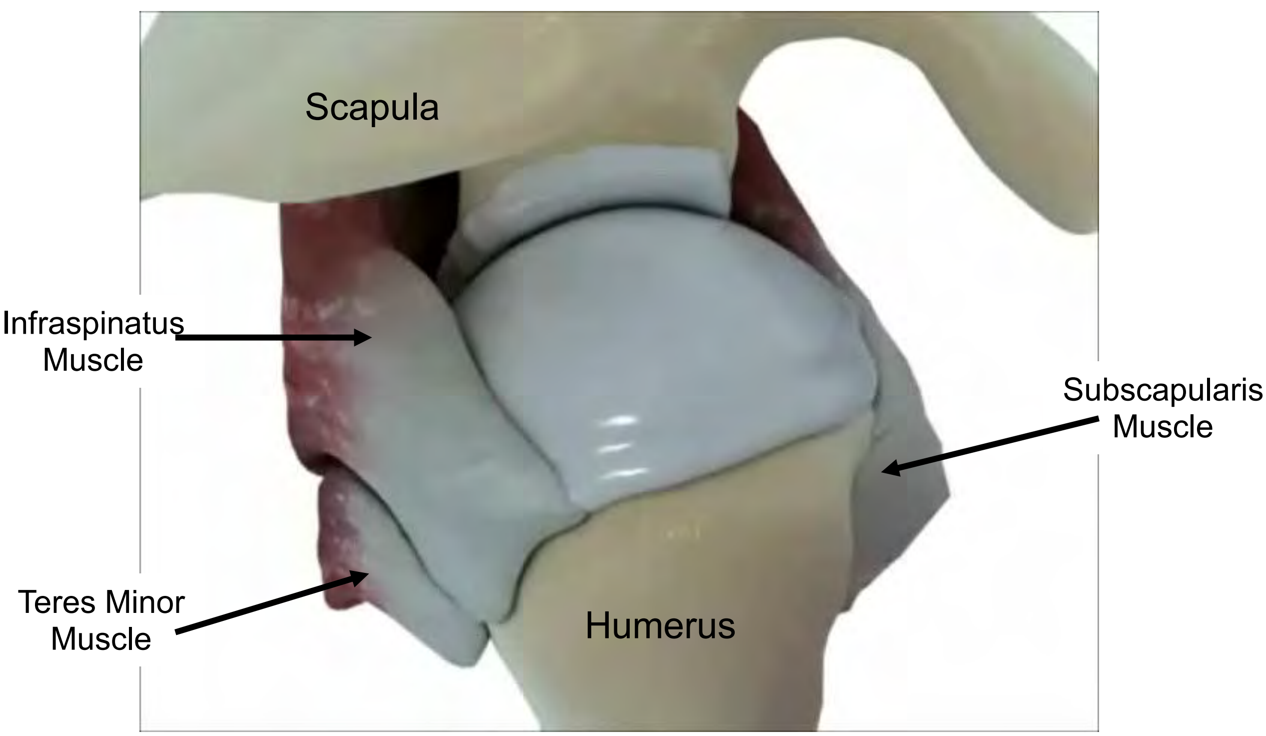

Figure 6. Right shoulder joint, viewed from lateral side. Available at commons.wikimedia.org

The shoulder contains many tendons; however, the supraspinatus and biceps tendons are the two most important for the CT technologist to understand. The supraspinatus tendon is the most frequently injured tendon of the rotator cuff; it runs underneath the acromioclavicular joint and continues over the humeral head. The biceps tendon, which runs through the bicipital groove and inserts on the glenoid labrum, provides additional support to the shoulder.

The primary bursae of the shoulder are the subacromial and subdeltoid. These two structures connect to form the largest bursa in the body. The bursae serve to cushion the tendons and ligaments—in this instance of the shoulder joint—and reduce friction between the tendons and bones. Bursae are lined with synovial membrane and contain synovial fluid.

The Sternum

The sternum consists of three components (**Figure 7**). The manubrium—the most superior portion of the sternum—articulates with the first two ribs, as well as the clavicles, which create the sternoclavicular (costosternal) joints. The sternal notch is located on the superior border of the manubrium. The manubrium and body of the sternum come together at the sternal angle, located at approximately the level of the fourth or fifth thoracic spine (T4-T5). The body of the sternum contains indentations along its sides that articulate with the third through seventh ribs. The xiphoid process forms the inferior border of the sternum; it serves as a site for muscle attachments and is commonly used as a landmark for localizer scans.

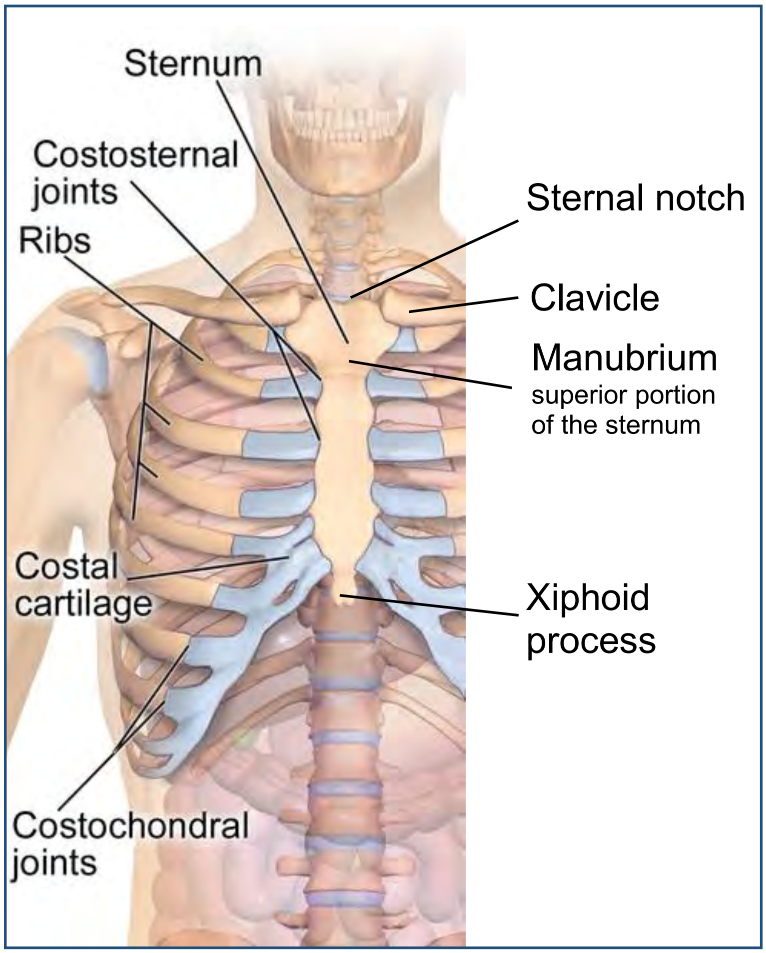

Figure 7. Anterior view of the bony thorax, illustrating the rib cage, sternum, and clavicles.
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The Elbow

The elbow is a hinge-pivot joint that is comprised of three large bones: the distal humerus, proximal radius, and proximal ulna (**Figure 8**).

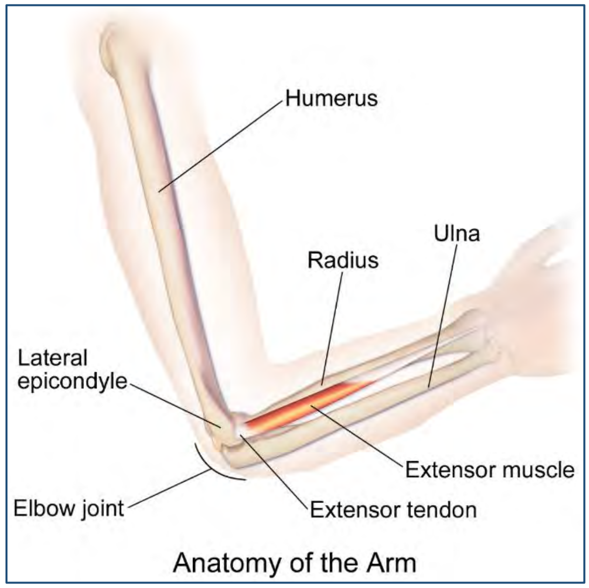


Figure 8. Anatomy of the arm.
Available at commons.wikimedia.org

The distal humerus has two distinct prominences, two depressions, and two articular surfaces. The prominences are called the medial and lateral epicondyles and serve as attachment sites for tendons and ligaments of the forearm. The two depressions are the coronoid fossa, which lies on the anterior surface of the humerus and accommodates the coronoid process of the proximal ulna, and the olecranon fossa on the posterior surface of the distal humerus, which accommodates the olecranon process of the proximal ulna. The capitellum articulates with the radial head, while the trochlea articulates with the proximal ulna.

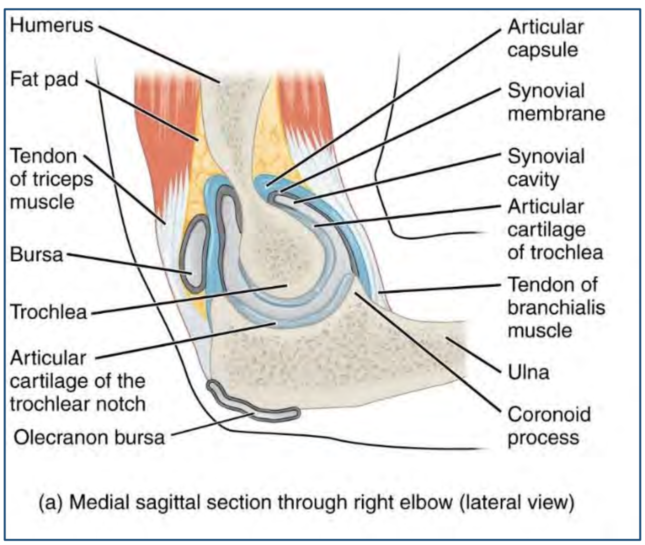
The radius is located in the forearm on the lateral side (side of the thumb) of the elbow. The head of the radius is roughly cylindrical; it relates to the lateral surface of the lateral portion of the distal humerus. The ulna, which is the medial (side of the pinky finger) bone of the forearm, is the smallest of the three arm bones. The ulna has a large olecranon process that forms a broad socket where the medial portion of the distal humerus sits.

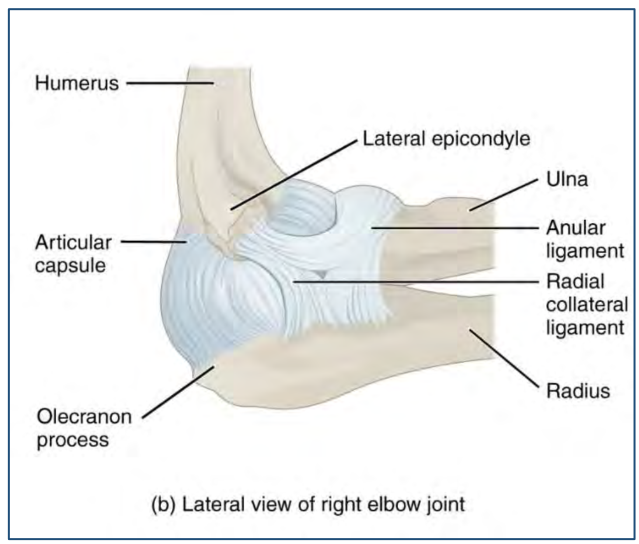
Two sets of articulations constitute the elbow joint. The radioulnar and radiohumeral articulations create a pivot joint that aids in supination and pronation of the forearm, while the ulnohumeral articulations form a hinge joint that allows flexion and extension.

Stability of the elbow is supplied by the collateral ligaments. The ulnar collateral ligament reinforces the medial side of the elbow, while the radial collateral ligament reinforces the lateral side. The annular ligament binds the radial head to the radial notch of the ulna (**Figure 9**).

A number of muscles and tendons originate and insert at the elbow. These are organized into four groups, according to location: the anterior, posterior, lateral, and medial groups. The anterior group consists of the biceps brachii and the brachialis, both of which flex the forearm; the biceps brachii additionally serves to supinate the forearm. The posterior group consists of the triceps brachii—which is the main extensor of the forearm—and the anconeus muscles, which pronate the ulna. The lateral group is made up of the brachioradialis muscle, which is the most superficial of the lateral group and is the flexor muscle for the forearm; the extensor muscles (several individual muscles that insert at various locations in the hand, but appear as a single muscle at the level of the elbow); and the supinator muscles, which supinate the forearm. The medial group includes the pronator teres (which provides pronation of the forearm and flexion of the elbow) and the flexor muscles of the fingers and wrist.

The primary blood supply to the elbow is provided by the brachial artery. The brachial artery can be visualized in the antecubital fossa on the anterior surface of the elbow. Finally, the most significant nerve for CT scanning purposes is the ulnar nerve. The ulnar nerve is the nerve most frequently injured due its superficial location between the medial epicondyle and olecranon process. The electric sensation felt when you hit your elbow (the "funny bone") is the direct result of stimulation of the ulnar nerve.





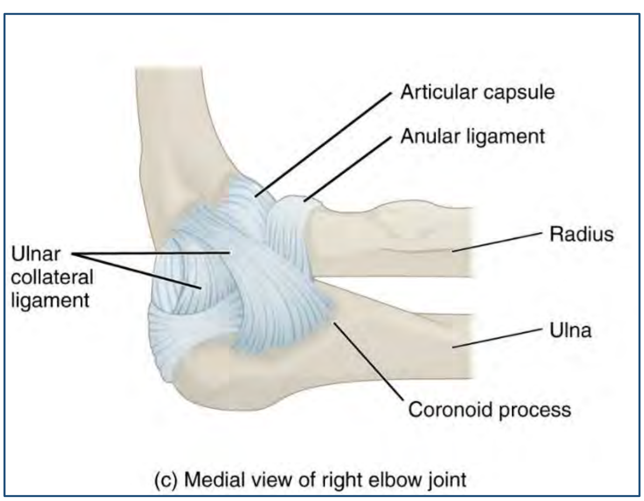


Figure 9. Illustrations of the elbow joint, showing muscles, tendons, and ligaments.
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The Wrist

The bones that form the wrist are the distal radius, distal ulna, and the eight carpal bones (**Figures 10 and 11**).

The distal radius and ulna are attachment sites for the muscles and tendons of the wrist; the radial styloid process is located on the lateral surface of the radius and the ulnar styloid process is on the posteromedial surface of the ulna. The carpal bones are divided into two rows: proximal and distal. The proximal row includes the scaphoid, lunate, triquetrum, and pisiform bones. The distal row consists of the trapezium, trapezoid, capitate, and hamate bones. The carpal tunnel is created by the concave arrangement of the carpal bones, which provides an enclosure for the passage of tendons and the median nerve. The complex motion of the hands requires the aid of numerous muscles arising in the forearm. However, the muscles exert their force through the tendons, which proceed from the muscles just before the wrist joint. The tendons are divided into two groups: the palmar tendon group flexes the fingers and passes through the carpal tunnel, and the dorsal tendon group extends the fingers and wrist and spans the superficial surface of the wrists (**Figure 12**).

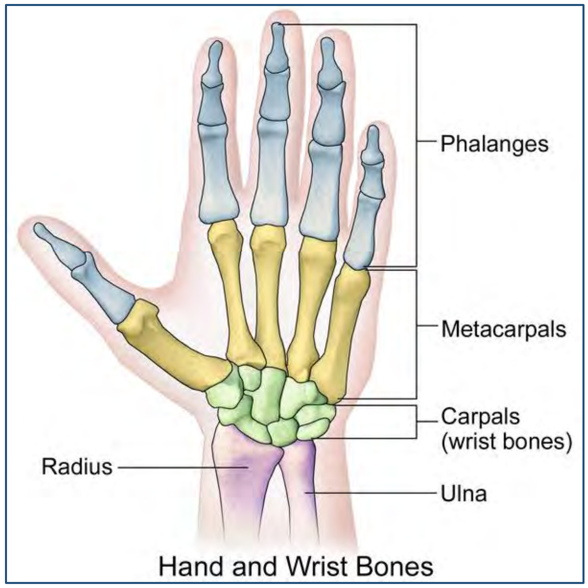

Figure 10. (Top) Illustration of the hand and wrist bones.
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Figure 11. (Bottom) Multiplanar reconstructions of the wrist. (A) Coronal and (B) Axial.

The wrist also contains numerous ligaments, which add stability to the joints. There are four major groups: the fibrocartilage complex, the major stabilizing element of the distal radioulnar joint; the intercarpal ligaments, which support the articulations between carpal bones; the radial collateral ligaments that provide lateral support to the wrist; and the ulnar collateral ligaments, which provide medial support to the wrist. These ligaments are readily visualized using MRI, while CT scanning is not as effective for evaluation of ligamentous injury.

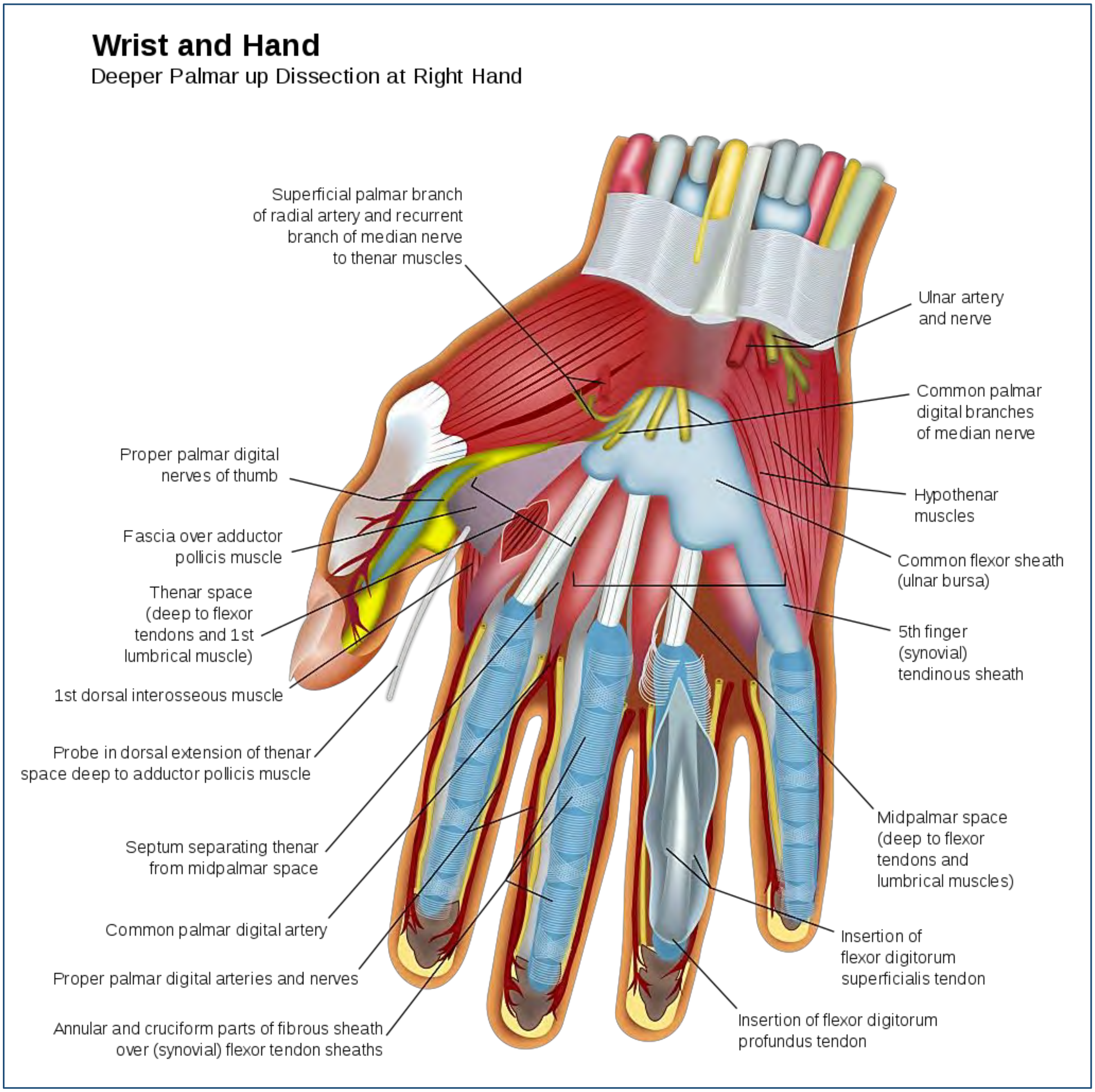


Figure 12. Illustration of anatomy of the hand, including muscles, nerves, vessels, and tendons. Available at commons.wikimedia.org

Blood is delivered to the wrist via the ulnar and radial arteries, while the ulnar and median nerves provide neurological functions. The ulnar artery and ulnar nerve are both located on the palmar medial side of the wrist. The location of the radial artery is generally well known, as it is the vessel that is used to detect a person's pulse. The median nerve passes through the carpal tunnel, usually superficial to the flexor tendons.

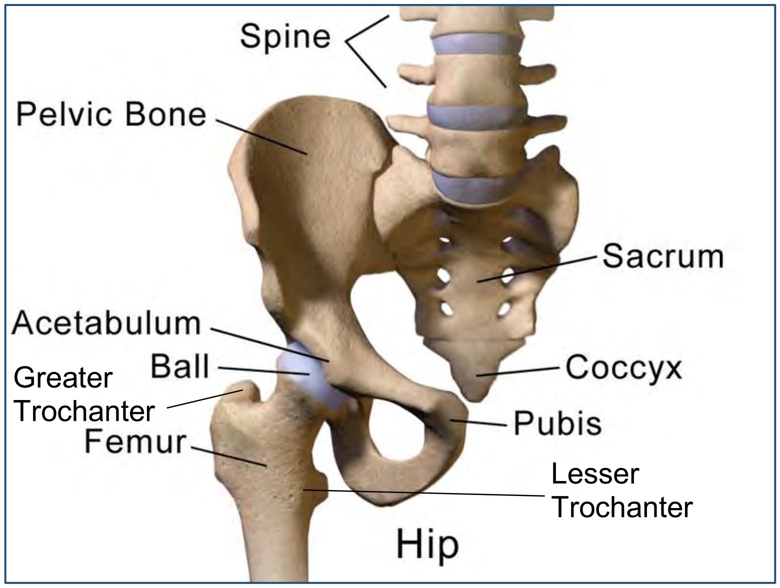


Figure 13. Illustration of hip anatomy; note articulation of the femoral head with the acetabulum at the site of the ball-and-socket joint. Available at commons.wikimedia.org

LOWER EXTREMITY JOINTS

The Hip and Pelvis

The hip is a ball-and-socket joint strong enough to carry the weight of the body in the erect position, yet allows for a wide range of motion. The hip joint is created by articulation of the femoral head with the acetabulum, also called the hip bone (**Figure 13**).

The acetabulum is composed of portions of three bones of the pelvis: the ilium, ischium, and pubis (**Figure 14**). In axial cross-sections, the acetabulum is divided into an anterior and posterior column. At the center of the acetabulum is the acetabular fossa, in which sits the femoral head and the principal ligaments of the joint.

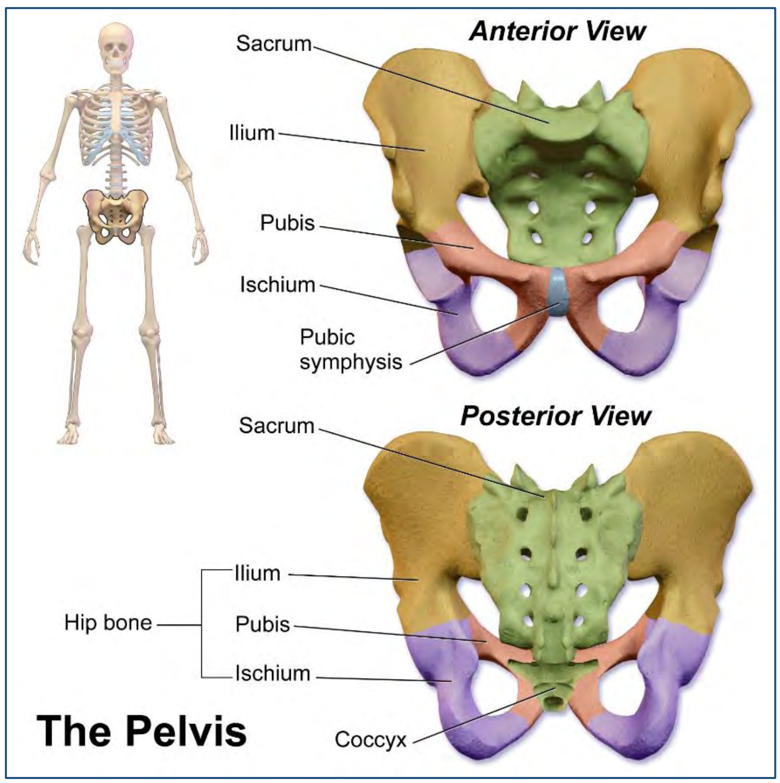


Figure 14. Illustration of the pelvis. Available at commons.wikimedia.org

The femoral head is rounded and smooth. It is covered by articular cartilage except at the fovea capitis, a small, centrally located pit that serves as a ligamental attachment site and a route for blood vessels to the femoral head. The femoral neck attaches the femoral head to the femoral shaft. At the distal end of the femoral neck are two large bony prominences: the greater trochanter on the lateral surface, and the lesser trochanter on the medial surface.

The femoral head is secured within the acetabulum by several major ligaments. The acetabular lip (or labrum) creates a fibrocartilaginous rim that is attached to the margin of the acetabulum. It closely surrounds the femoral head and helps hold it in place.

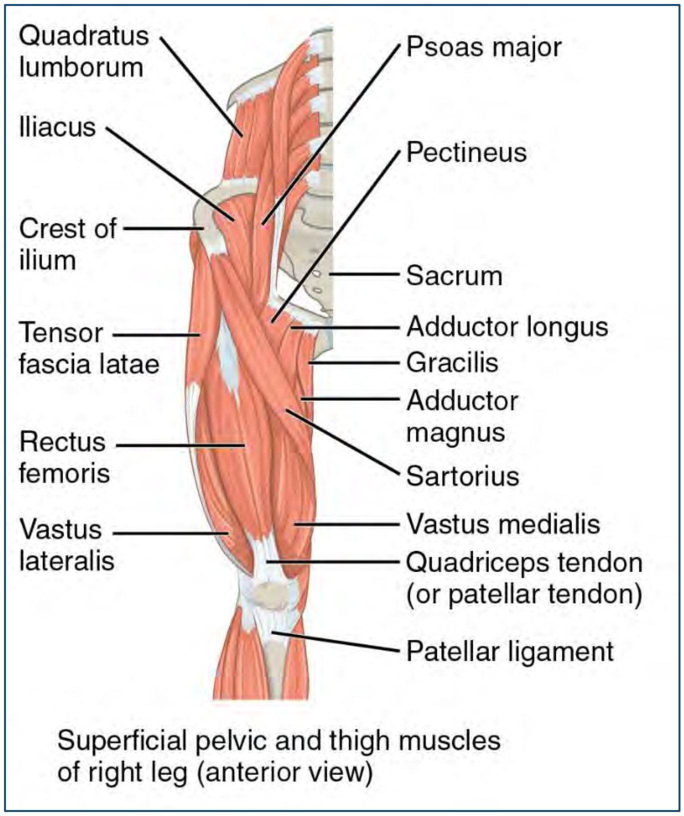
The transverse ligament reinforces the inferior margin of the acetabulum, and forms a portion of the acetabular labrum.

The major ligaments that support the hip joint are the iliofemoral ligament, ischiofemoral teres, pubofemoral teres, and ligamentum teres.

The hip joint is served by anterior, posterior, medial, and lateral muscle groups. The anterior group (**Figure 15)** is comprised of the quadriceps femoris, a powerful extensor that inserts on the patella and extends the knee; the iliopsoas, the strongest flexor of the hip; and the sartorius, which is the longest muscle in the body and flexes and rotates the leg. The posterior muscle group consists of the lateral rotators of the thigh: the obturator internus, obturator externus, quadratus femoris, and piriformis. The medial muscle group provides adduction of the thigh; these muscles include the pectineus, adductor, and gracilis muscles. The lateral muscle group consists of the three gluteus muscles. The largest, the gluteus maximus, serves as an extensor of the thigh, while the gluteus medius and gluteus minimus abduct and medially rotate the thigh. Finally, the tensor fasciae latae muscle, located on the outside lateral part of the hip, provides flexion and abduction of the hip.

The hip is served by the sciatic nerve and femoral artery. The sciatic nerve is the largest peripheral nerve in the body and emanates from the sacral plexus of nerves. The sciatic nerve travels through the posterior portion of the pelvis, exiting at the greater sciatic foramen; it then continues along the posterior aspect of the lower extremity. The sciatic nerve carries nerve fibers from each of the lumbar interspaces, but most prominently from the L3-L5 space, explaining why lumbar disc herniation produces pain along the course of the sciatic nerve. The sciatic nerve innervates the thigh and all muscles in the leg and foot. The femoral artery is an extension of the external iliac artery and is located lateral to the femoral vein. The femoral artery is a critical vessel; it is prone to atherosclerosis but, more importantly, it is the major arterial entrance for most angiographic and interventional catheter-based procedures.

The pelvis provides structural support for the body and encloses the male and female reproductive organs. The bones of the pelvis include the sacrum and coccyx of the spinal column, and the ilium, ischium, and pubis. (The sacrum and coccyx are discussed in greater detail in Chapter 3.) The ilium is the largest and most superior portion of the pelvis. The body of the ilium is a large, wing-like bone (iliac wing) with a concave anterior surface (the iliac fossa), a superior ridge (the iliac crest), and inferior and lateral iliac spines. The body of the ilium creates the upper portion of the acetabulum. Posteriorly, both iliac bones join either side of the sacrum to form the right and left sacroiliac joints.



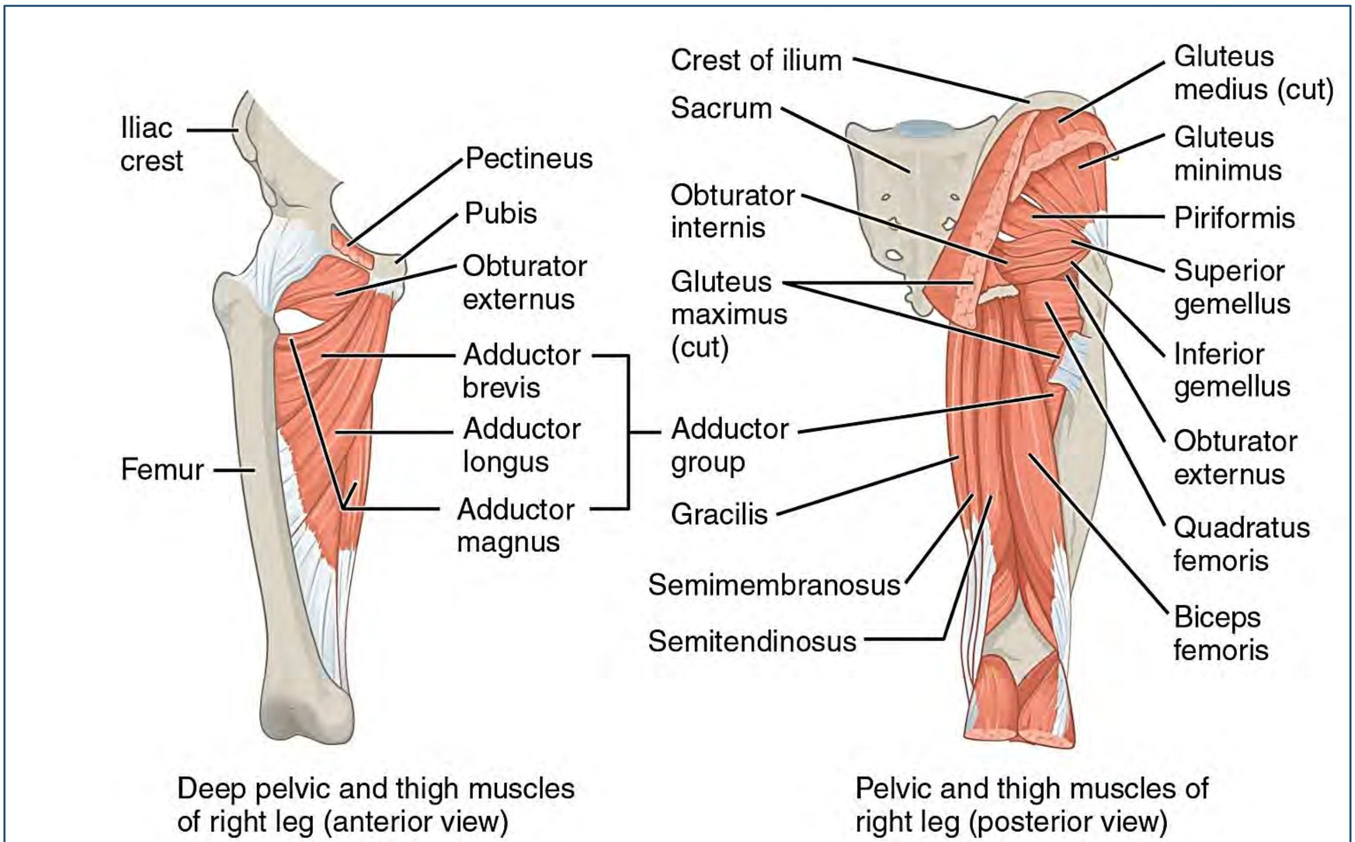


Figure 15. Illustration of the hip, thigh, and pelvic muscles. Available at commons.wikimedia.org

As illustrated in Figures 13 and 14, the pubis, or pubic bone, forms the lower anterior portion of the acetabulum; it consists of a body, a superior pubic ramus that extends laterally from the body to meet the ilium, and an inferior pubic ramus that extends inferiorly from the body to meet the ischium. The two pubic rami meet at the midline to form the pubic symphysis, a cartilaginous joint that connects the left and right portions of the pelvis.

The ischium is composed of a body, which forms the lower posterior portion of the acetabulum, and two rami. The superior ischial ramus extends posteriorly and inferiorly to the ischial tuberosity. The inferior ischial ramus extends anteriorly and medially from the ischial tuberosity to join the inferior pubic ramus. The ischial spine projects from the superior ischial ramus between two prominent notches, the greater and lesser sciatic notches. These notches are spanned by ligaments that create foramens for the passage of the sciatic nerves and gluteal vessels. The union of the pubic rami and the ischium forms a large ring-shaped opening called the obturator foramen.

The muscles of the pelvis consist of the extrapelvic muscles, the muscles of the pelvic wall, and the pelvic diaphragm. The extrapelvic muscles are actually extensions of the abdominal and retroperitoneal muscles into the pelvis. They consist of the rectus abdominis, which extends from the symphysis pubis to the xiphoid process and supports the abdomen; the internal and external oblique muscles, located on the outer lateral portion of the abdomen—these muscles work together to flex the vertebral column and compress the abdominal viscera; and the psoas muscles, which extend along the lateral surface of the lumbar spine. The psoas muscles join the flat iliacus muscles along the inner border of the iliac wing, forming the iliopsoas muscle in the pelvis. In addition, the gluteal muscles of the hip can also be visualized in the pelvis.

The muscles of the pelvic wall are the piriformis and obturator internis, which rotate the thigh laterally; the obturator externus, which aids in adduction and rotation of the thigh; and the iliacus, which joins the psoas muscle to form the iliopsoas muscle. Finally, the pelvic diaphragm is a layer of muscle that forms the majority of the pelvic floor.

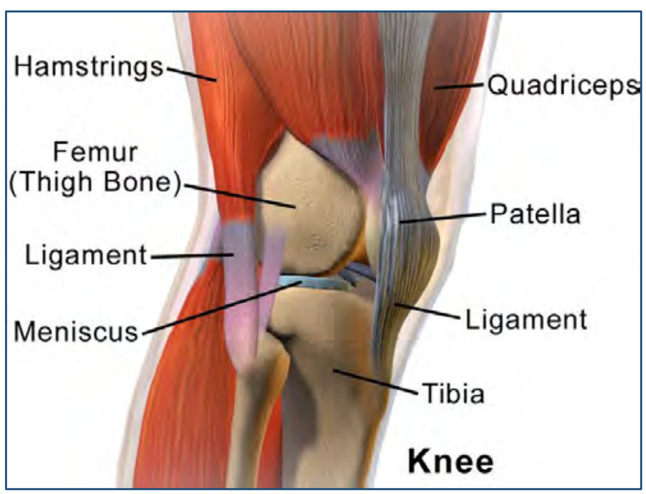


Figure 16. Illustration of the anatomy of the knee, side view. Available at commons.wikimedia.org

The Knee and Leg

The knee is a complex hinge joint consisting of the distal femur, proximal tibia, proximal fibula, and the patella (**Figure 16**). The distal femur contains two projections—the medial and lateral condyles—that articulate with the tibia at the tibial plateaus. These plateaus are flattened surfaces on the superior tibia separated by the tibial spine (intercondylar eminence). The tibial tuberosity is a roughened area on the anterior surface of the top of the tibia that provides an insertion site for the patellar ligament (**Figure 17**). The patella, the largest sesamoid bone in the body, is located on the anterior surface of the knee joint; it protects the knee and increases the leverage of the quadriceps extensor (**Figure 18**).

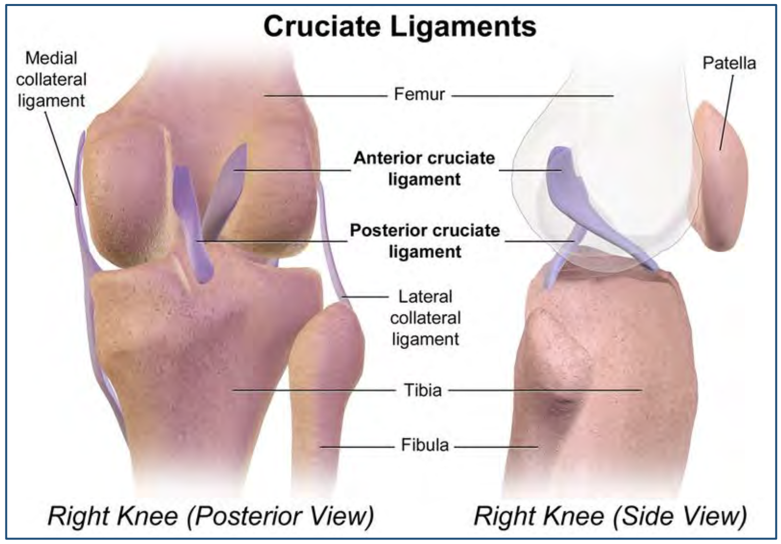


Figure 17. Illustration of the knee cruciate ligaments. Available at commons.wikimedia.org

The knee incorporates a complex system of cartilage and ligaments that connect and cushion the joint. Cartilage completely covers the articular surfaces of the femur, tibia, and patella to provide smooth movement within the knee joint. The C-shaped menisci, composed of fibrous connective tissue, cushion the articulation of the femoral condyles and tibial plateaus. In addition, three sets of ligaments provide support for the knee. The collateral ligaments reinforce the joint capsule on the medial and lateral sides. The anterior and posterior cruciate ligaments provide stability on those aspects of the knee, with the anterior cruciate ligament also preventing displacement of the tibia. The patellar ligament helps maintain the position of the patella in the knee joint. Visualization of the ligaments and menisci in the knee joint is best performed using MRI, rather than CT.

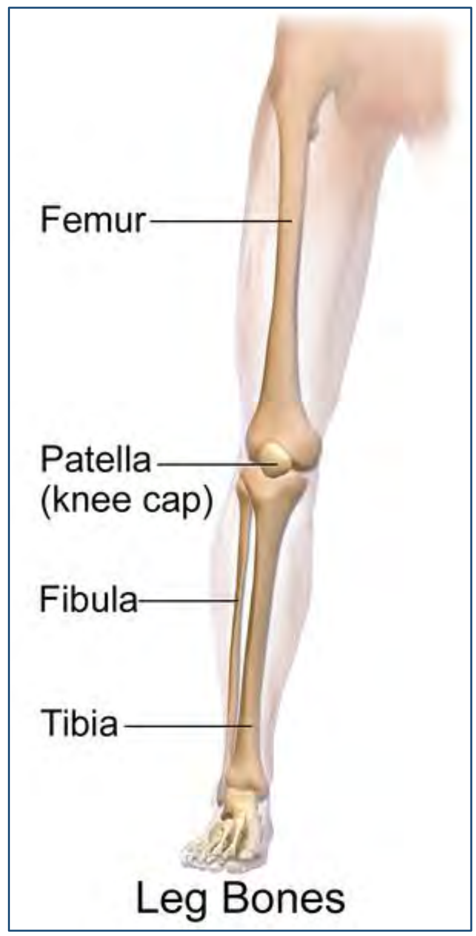
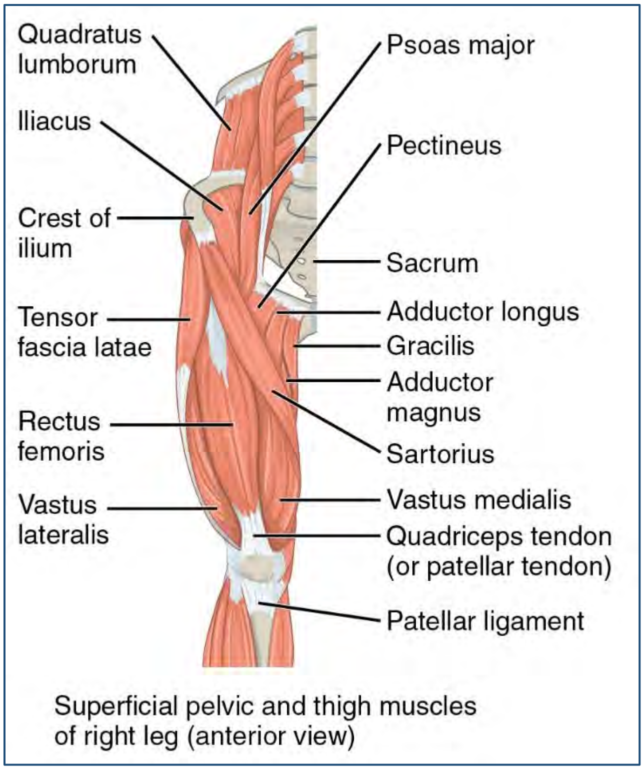


Figure 18. Illustration of the bones of the leg, anterior view. Note the sesamoid-shaped patella. Available at commons.wikimedia.org



The muscles of the knee and leg are the quadriceps, hamstrings, popliteus, and gastrocnemius (**Figures 19-20**). The quadriceps femoris is the largest muscle group in the body, covering almost all of the anterior surface and sides of the femur, and functions as a very powerful extensor of the leg. The three hamstring muscles span the posterior aspect of the hip and knee joints and serve as extensors of the thigh and flexors of the leg. The popliteus muscles flex the leg and rotate the femur laterally, while the gastrocnemius muscle, a prominent flexor of the leg, spans the posterior aspect of the knee. The gastrocnemius inserts on the calcaneus via the Achilles tendon.

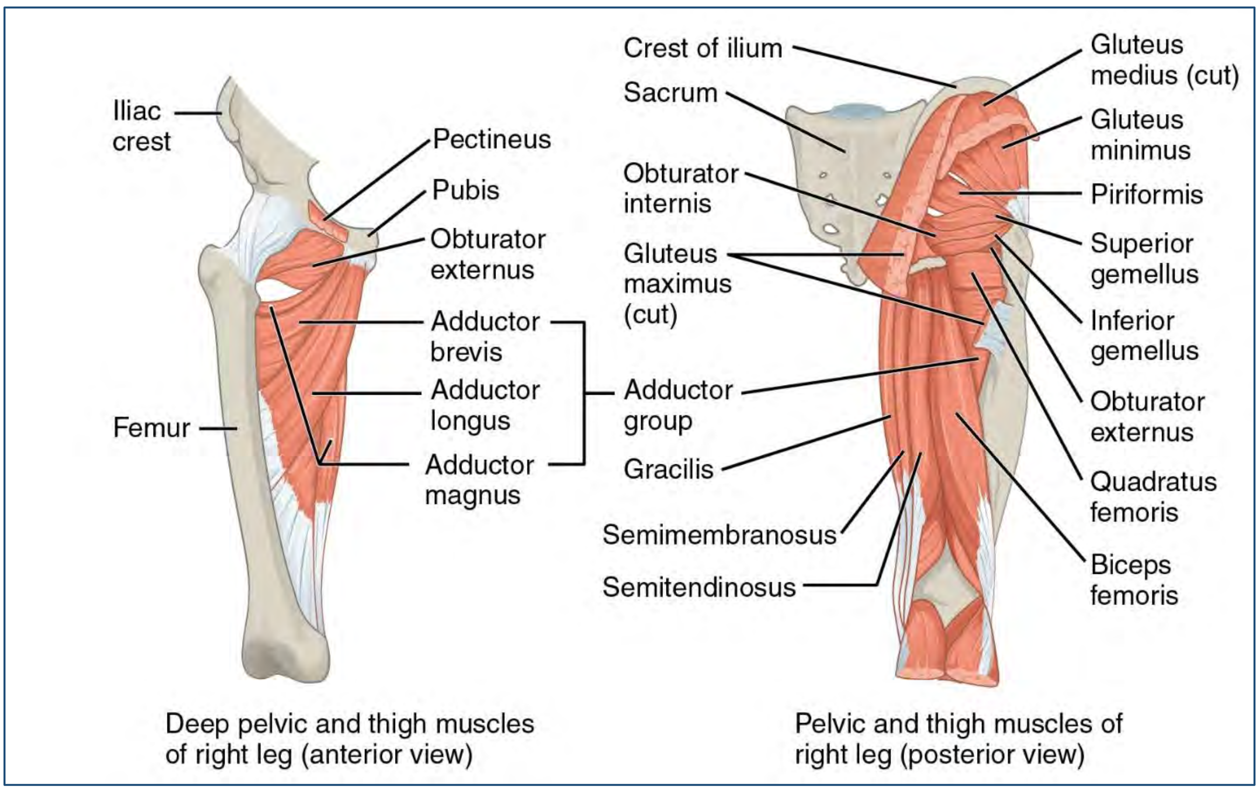


Figure 19. Illustration of thigh and pelvic muscles. Available at commons.wikimedia.org

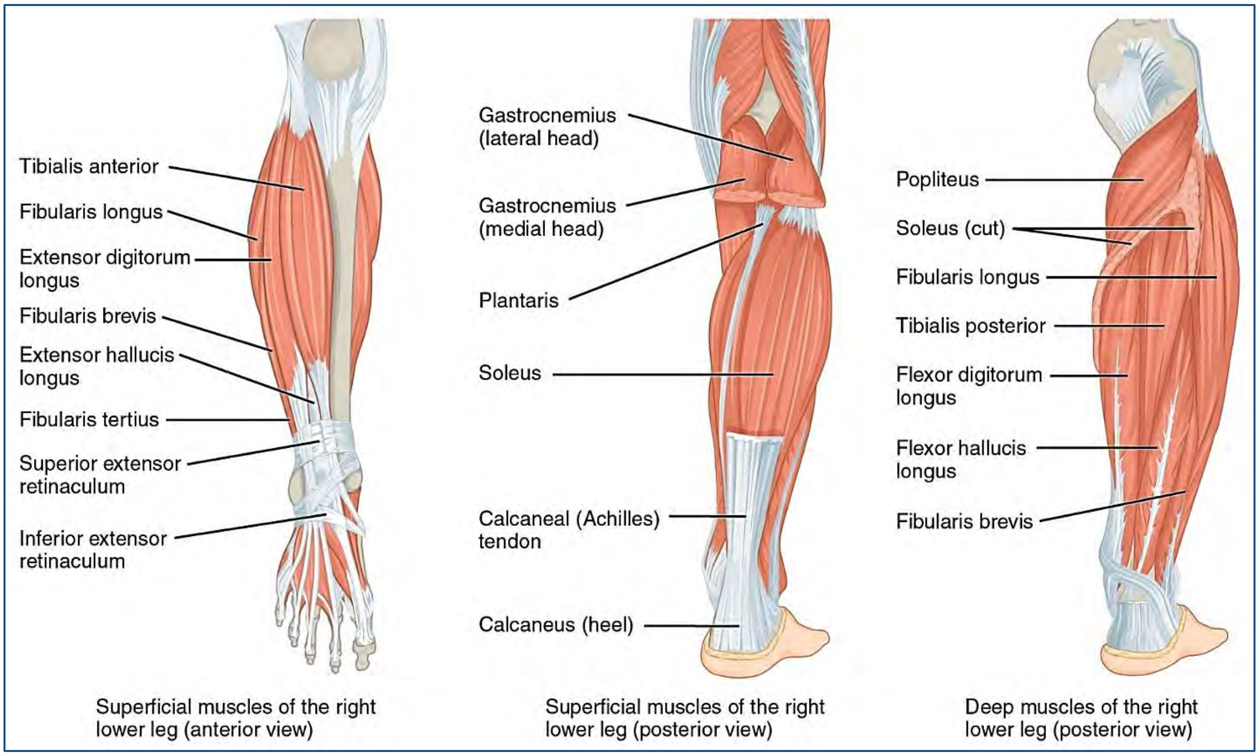
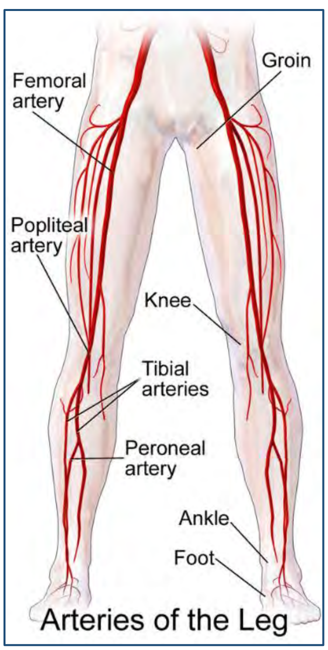


Figure 20. Illustration of muscles of the lower leg. Available at cnx.org

The primary blood vessels of the knee and leg are the popliteal artery and vein, which lie within the popliteal fossa in the back of the knee (**Figure 21**). The popliteal artery divides into three branches (the anterior and posterior tibial arteries and the peroneal artery) that supply blood to the lower extremity and foot. The major popliteal vein runs concurrent to the popliteal artery and drains into the deep femoral system. The popliteal vein is the major source of thrombi leading to pulmonary embolism.



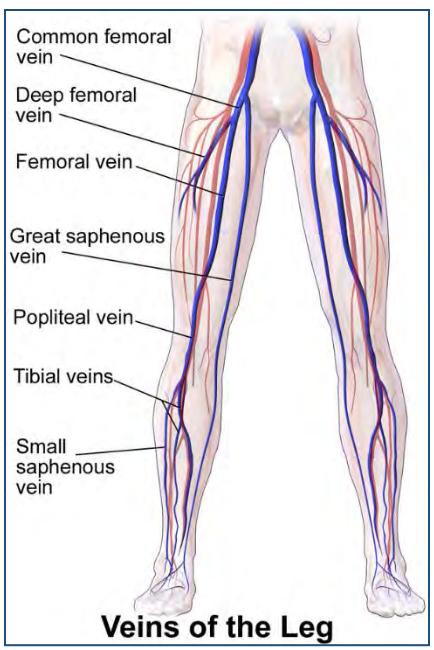


Figure 21. (Left) Illustration of the arteries of the leg.
Available at commons.wikimedia.org

(Right) Illustration of the veins of the leg.
Available at commons.wikimedia.org

The Ankle and Foot

The ankle is a hinge-like structure that allows complex movement and balance of the foot (**Figure 22**). The bones of the ankle are formed by articulations between the tibia and fibula at their distal terminations. The distal tibia contains a process called the medial malleolus, and the distal fibula likewise contains a process called the lateral malleolus; both of these are located at essentially the same level. The medial and lateral malleolus serve as sites for muscle attachment.

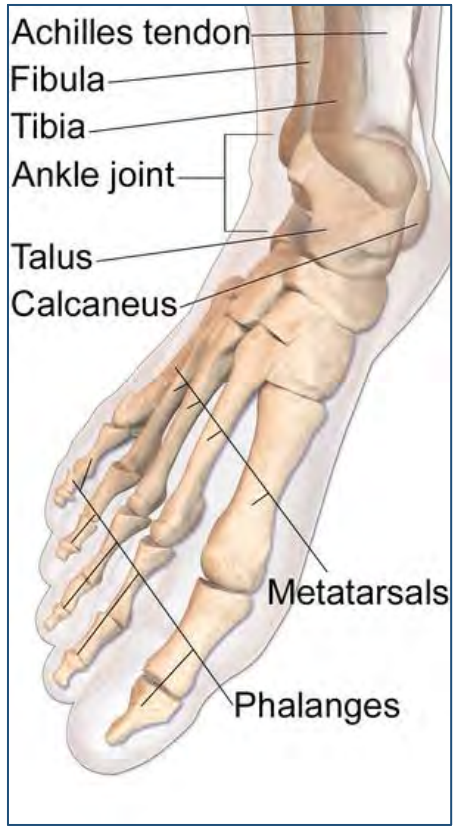


Figure 22. Illustration of the ankle and foot. Available at commons.wikimedia.org

The distal tibia and fibula both articulate with the trapezoid-shaped talus (**Figure 23**). The entire weight of the body is transferred to the foot across this thick bone. The talus rests on the calcaneus, which is the largest and thickest bone of the foot and forms the heel. The talus and calcaneus communicate at the subtalar joint; this joint is composed of three articulations: the anterior facet, the middle facet (which provides weight-bearing support to the medial side of the ankle), and the posterior facet (which provides support for most of the body of the talus). Between the middle and posterior facets lies the tarsal canal, containing blood vessels, fat, and the interosseous ligament.

The tarsal bones of the foot are the cuboid, navicular, and cuneiform. The cuboid bone lies lateral and anterior to the ankle, and articulates anteriorly with the base of the fourth and fifth metatarsals. The navicular bone articulates posteriorly with the talus, and anteriorly with the cuneiform bones on the medial side of the foot. The three cuneiform bones are numbered consecutively from medial (1) to lateral (3); these articulate anteriorly with the first three metatarsal bones.

Multiple ligaments provide structural support to the bones of the ankle (**Figure 24**). The deltoid ligament—the strongest ligament in the ankle— arises from the medial malleolus and fans out into three bands, providing medial support to the ankle. The lateral ligaments originate at the fibular malleolus, and insert into adjacent bone structures. The plantar ligament, also called the spring ligament, maintains the longitudinal arch of the foot, while the interosseus ligament binds the talus to the calcaneus.

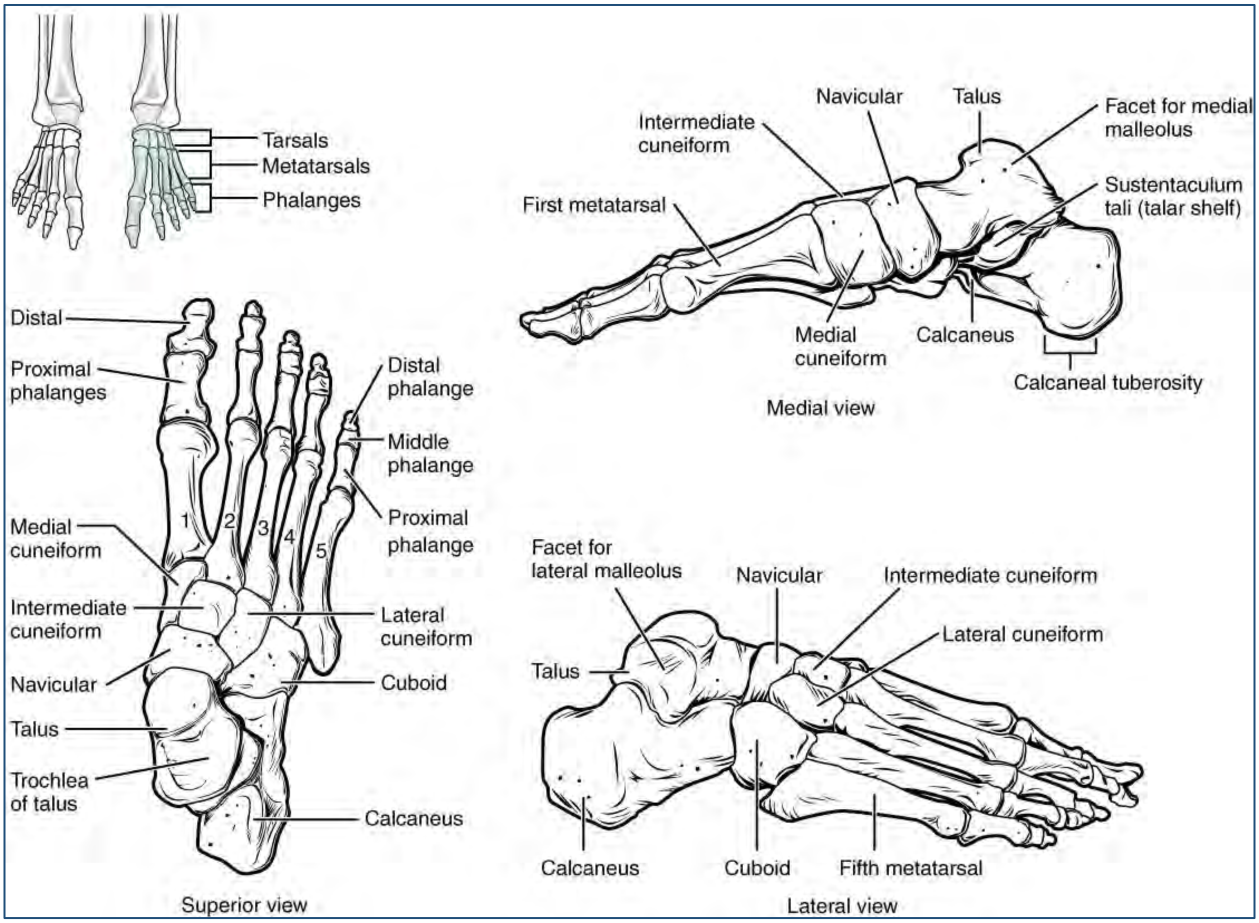


Figure 23. Bones of the foot. Available at [wikimedia.org]

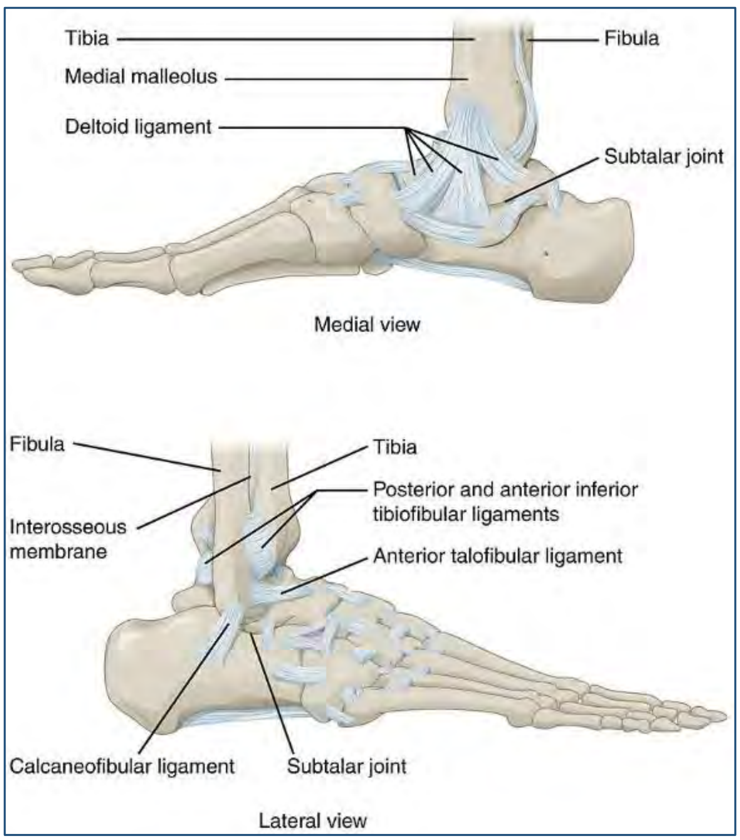


Figure 24. Illustration of ligaments of the foot. Available at [commons.wikimedia.org]

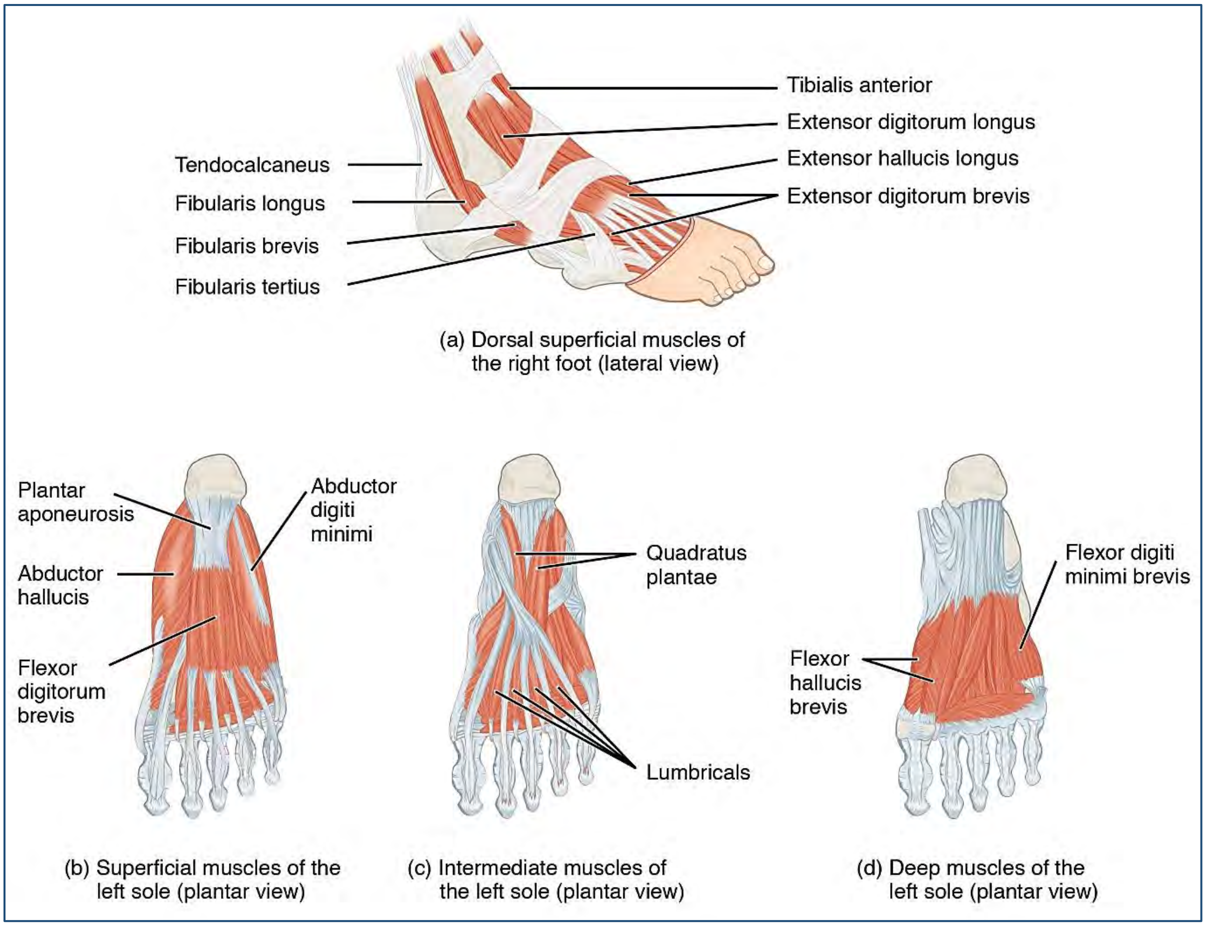


Figure 25. Illustration of muscles of the feet. *Available at* cnx.org

Four groups of tendons connect the muscles and bones of the foot (**Figure 25**). The posterior group consists only of the Achilles tendon, the largest and most powerful tendon in the body (**refer to Figure 20**). The Achilles tendon connects the gastrocnemius muscle to the calcaneus and provides extension and dorsiflexion of the foot. The medial group of tendons provides inversion and plantar flexion of the foot, while the lateral group allows eversion and weak plantar flexion, and stabilizes the ankle joint laterally.

CLINICAL INDICATIONS AND IMAGING PROTOCOLS

Clinical indications for CT scanning of the musculoskeletal system can be divided into several categories:

- Evaluation of trauma and fractures
- Detection of metastatic disease
- Evaluation of arthritis
- Diagnosing infection
- Diagnosing or ruling out metabolic disease
- Pre- and post-surgical planning

The technologist must be aware of which imaging modality is the most appropriate for obtaining accurate information when imaging a trauma or post-surgical patient. High-quality CT scans can be obtained through a plaster cast; however, CT scans are extremely degraded in the presence of orthopaedic hardware. If there is significant hardware present, plain film evaluation may be superior to CT. MRI may also be a better choice than CT if the orthopaedic hardware is nonferromagnetic.

PROTOCOL DEVELOPMENT FOR CT MSK EXAMS

Development of MSK-specific CT protocols is a vital step in extremity imaging. Technologists and radiologists must work together to develop the best protocols at the lowest radiation dose to the patient. As discussed in Chapter 1, many modern scanners employ iterative reconstruction that can significantly decrease the radiation dose to the patient. However, applying *too much* IR can create an overly smooth, model-like image undesirable for evaluating fine bony details. Therefore, it is important that the radiologist is involved in protocol development to maintain image quality. Thin-section (1.25mm or less) helical imaging in the axial plane is necessary for evaluating fine bony details and for orthogonal, coronal, and sagittal multiplanar reconstructions. MPRs reconstructed from thicker sections can result in stepladder effect (**Figure 26**).

Thin-section axials can either be acquired during the scan or reconstructed from thicker section images. Images should be reconstructed in soft tissue and bone algorithms. At minimum, coronal and sagittal MPRs should be acquired. Specific information will be provided throughout the chapter about proper acquisition of orthogonal, coronal, and sagittal MPRs for each extremity and joint.

Figure 26. (A) MPR reconstructed from 5mm axial images results in stepladder artifact. (B) MPR reconstructed from 0.625mm axial images results in a good quality image.

CT scans on patients who have metallic orthopaedic hardware can be problematic because of beam-hardening effect and streak artifact. Protocol adjustments using projection-based metal artifact reduction (MAR) or dual-source imaging (DSI) can be considered when imaging patients with implants. MAR algorithms replace corrupted data caused by artifact with interpolation with neighboring uncorrupted data. DSI allows the technologist or radiologist to select high keV monochromatic images where beam-hardening effects are lessened. MAR algorithms may be applied *after* image acquisition, while the decision to use DSI must be made *before* scan acquisition.[1]

Not all scanners are equipped with MAR or DSI, so increasing the kVp is also a potential protocol adjustment for patients with metal orthopaedic devices. However, increasing kVp also decreases image contrast, so there is a potential cost to image quality.[2] Increasing the kVp level will also result in increased radiation dose to the patient. Hip, shoulder, and knee replacements create the most artifact and can be difficult to image even after increasing the kVp or using MAR or DSI.

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[1]. Katsura M, Sato J, Akahane M, Kunimatsu A, Abe O. Current and Novel Techniques for Metal Artifact Reduction at CT: Practical Guide for Radiologists. Radiographics. 2018;38(2):450-461.

[2] Kataoka ML, Hochman MG, Rodriguez EK, Lin PJ, Kubo S, Raptopolous VD. A review of factors that affect artifact from metallic hardware on multi-row detector computed tomography. Curr Probl Diagn Radiol. 2010;39(4):125-136.

CT SCANNING OF THE SHOULDER AND SCAPULA

Imaging of the shoulder and scapula are indicated:

- to determine the degree of fracture displacement from trauma
- to detect subtle fractures not seen on plain films
- to detect bone fragments or loose bodies within the joint
- in conjunction with CT arthrography to demonstrate the integrity of the bursa and rotator cuff, and/or to diagnose labral tears and synovial pathology

Multidetector-row CT with 3D volume rendering or 2D multiplanar reformatting is extremely sensitive and very useful for the detection and characterization of shoulder and scapula fractures. These techniques can display spatial relationships among the fracture fragments, the number of fragments, and their degree of rotation; this information is important to determine whether a fracture should be managed medically or surgically.

The patient is placed head first and supine into the scanner, with the affected arm at the side and the hand in the neutral position. An anteroposterior (AP) localizer scan should be obtained from above the acromioclavicular joint through the entire shoulder capsule. Using the scout image, the technologist identifies the center of the joint and the adjustments to the horizontal (*x*) and the vertical (*y*) axis necessary to place the shoulder in the center of a 16-20cm display field of view (**Figure 27**). Display slice thickness is typically 3-5mm, but may vary depending on the clinical indication. Images are reconstructed using both bone and soft tissue algorithms. Thin ≤1.25mm section helical images in the axial plane should be acquired or reconstructed for finer detail. Coronal, sagittal, and volume-rendered 3D images should also be acquired from thin-section image data. Iodinated contrast may be used to highlight various soft tissue masses as deemed necessary by the radiologist.

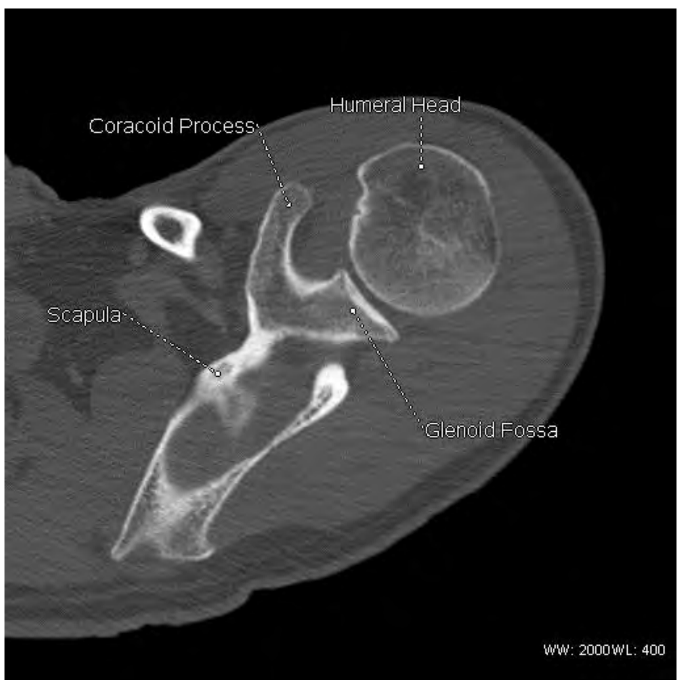

Figure 27. Axial image of the shoulder through the midjoint.

Multiplanar Reconstructions of the Shoulder

MPRs of the shoulder are planned using the glenohumeral joint line as a reference point. The arrows identify the glenohumeral joint line on a reference axial image **(Figure 28**).

- To obtain coronal MPRs, create a plane perpendicular to the glenohumeral joint line on the reference axial image (**Figure 29**).
- To obtain sagittal MPRs**,** create a plane parallel to the glenohumeral joint line on the reference axial image (**Figure 30**).
- To obtain *true* axial MPRs of the shoulder, identify the glenohumeral joint line on a reference coronal image and create a plane perpendicular to the line (**Figure 31**).

Figure 28. Reference axial image for planning MPRs of the shoulder.

Figure 29. Reference axial image for obtaining coronal MPRs of the shoulder.

Figure 30. Reference axial image for obtaining sagittal MPRs of the shoulder.

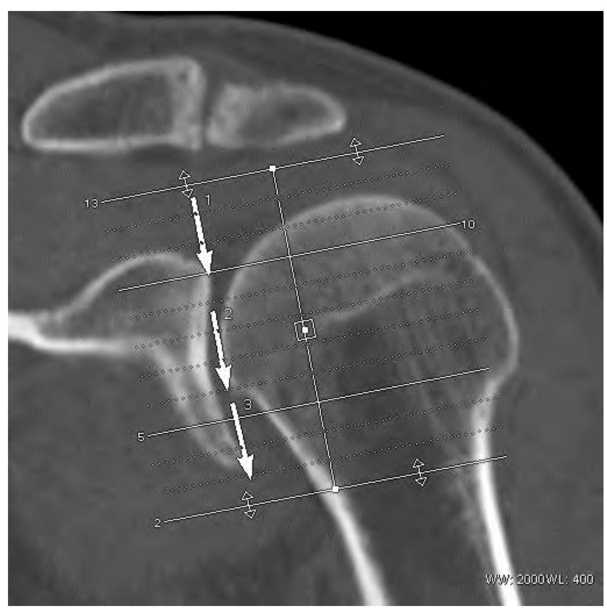

Figure 31. Reference coronal image for obtaining a true axial MPR of the shoulder.

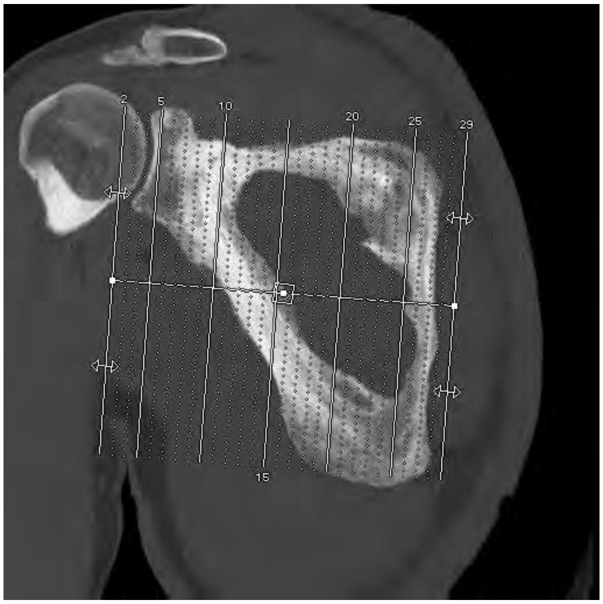

Figure 32. Sagittal MPRs are obtained by creating a plane perpendicular to the body of the scapula on a reference coronal image.

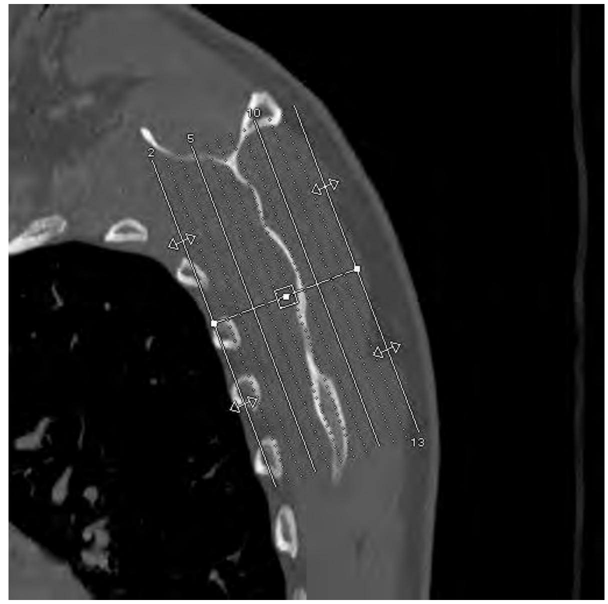

Figure 33. Coronal MPRs are obtained by creating a plane parallel to the body of the scapula on a reference sagittal image.

Multiplanar Reconstructions of the Scapula

- Sagittal MPRs are obtained by creating a plane perpendicular to the body of the scapula on a reference coronal image (**Figure 32**).
- Coronal MPRs are obtained by creating a plane parallel to the body of the scapula on a reference sagittal image (**Figure 33**).

CT SCANNING OF THE STERNUM

The most common reason to image the sternum is for evaluating sternal fracture. CT scans are also used to diagnose or rule out suspected infections or tumors in the sternum.

The patient should be placed head first and supine into the scanner, with the arms placed at the side, and instructed to maintain a breath-hold to minimize motion artifacts. It may be advantageous to hyperventilate the patient prior to breath-holding to ensure limited motion in the sternal area. Thin, 1.25mm axial images should be acquired or reconstructed for fine bony detail and for multiplanar reconstructions. MPR and/or 3D volume rendering (VR) images can help identify sternal displacement due to fractures and dislocation of the sternoclavicular joint. Scans are typically unenhanced, although IV contrast may be used if vascular trauma is suspected.

Most injuries to the sternoclavicular joint referred for CT are a result of blunt closed chest trauma, for example, in a motor vehicle accident. These fractures are often accompanied by fractures of the superior ribs or shoulder joint.

Posterior dislocation of the sternoclavicular joint is commonly associated with injury to the aorta or great vessels; in such cases IV contrast should be given to exclude vascular injury (**Figure 34**).

Figure 34. Sternal images showing anatomy. (A) Curved coronal reformat showing the entire sternum in one image; (B) coronal MPR; (C) sagittal MPR.

Multiplanar Reconstructions of the Sternum

- Sagittal MPRs of the sternum are obtained by creating a plane perpendicular to the body on a reference coronal image (**Figure 35**).
- Coronal MPRs of the sternum are obtained by creating a plane parallel to the body on a reference sagittal image (**Figure 36**).
- Due to the curved shape of the sternum, coronal images may also be obtained by creating curved multiplanar reformats on a reference sagittal image or curved coronal reformatted image (**Figure 37**).

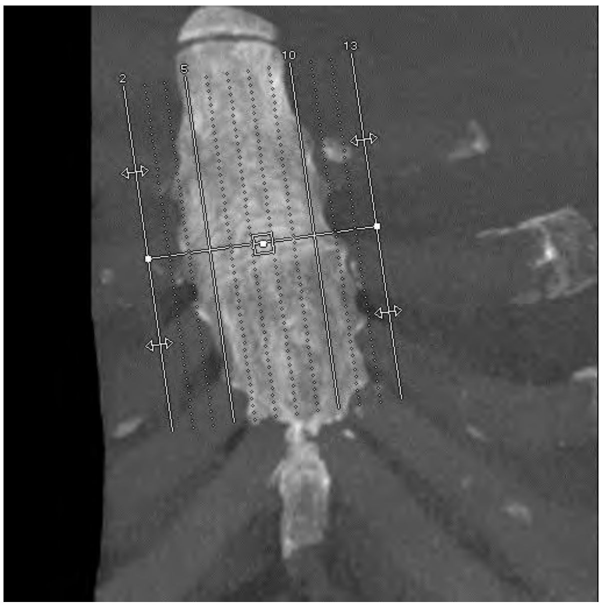

Figure 35. Reference coronal image for obtaining sagittal MPRs of the sternum.

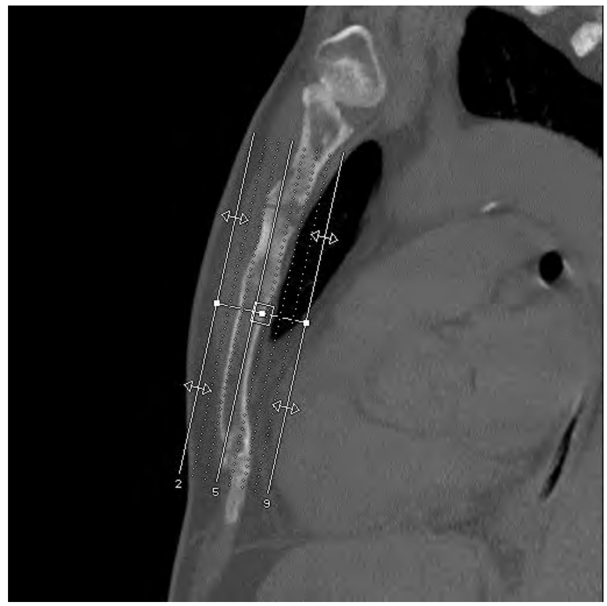

Figure 36. Reference sagittal image for obtaining coronal MPRs of the sternum.

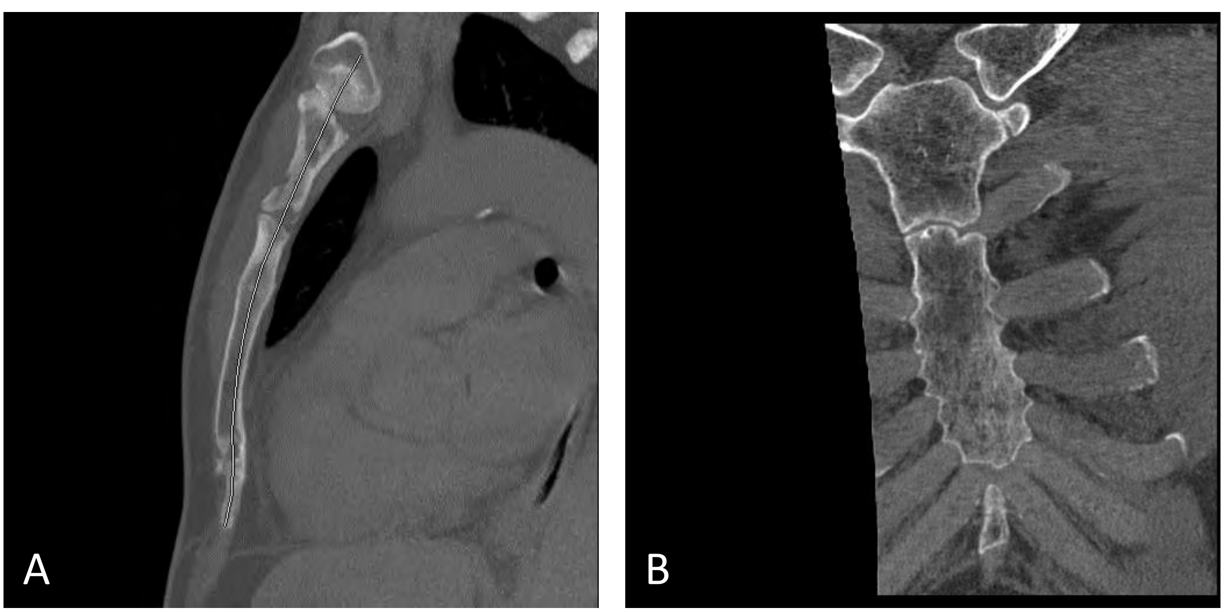

Figure 37. (A) Curved MPR on a reference sagittal image of the sternum; (B) curved coronal reformatted image.

A Note About Orthogonal Reconstructions of Long Bones in Both the Upper and Lower Extremities

“Orthogonal” means at right angles, and an orthogonal projection or view is a radiograph obtained at 90º to the original view. When creating sagittal and coronal images of long bones like the humerus, ulna, and radius in the upper extremities, and the femur, tibia, and fibula of the lower extremities, orthogonal planes must be created.

The same principle applies to *all* long bones.

CT SCANNING OF THE ELBOW AND ARM

Scanning of the Humerus

For CT scanning of the humerus, the patient should raise the unaffected arm above the head. Patients with broad shoulders may need to be offset to better center the area of interest in the gantry.

- Obtain an orthogonal sagittal MPR of the humerus by creating a plane perpendicular to the reference coronal image (**Figure 38**).
- Obtain an orthogonal coronal MPR of the humerus by creating a plane parallel to the reference sagittal image (**Figure 38**).

Additional images of the humerus can be found later in this material in the section titled *Multi-oblique Reconstructions*.

Figure 38. Orthogonal reconstructions of the humerus. (A) Orthogonal sagittal MPR; (B) orthogonal coronal MPR.

Scanning of the Elbow

CT scanning of the elbow is indicated in cases of fracture where findings on conventional radiography are equivocal, or for more precise visualization of complex fractures. 3D VR or 2D MPR images aid in depicting the fracture-fragment interrelationships. Data sets can even be acquired on a patient with a plaster cast. CT arthrography can be performed following the injection of contrast material into the elbow joint; however, current MRI and 3D CT techniques are beginning to replace the use of CT arthrography. Use of contrast will highlight an abscess but should first be deemed necessary by the radiologist.

With a single-slice scanner, two acquisitions are required to attain both axial and coronal images. The patient is positioned head first and prone, with the affected arm fully extended above the head. Axial images are obtained with the palm down, rotating the radius and ulna to achieve better visualization of the proximal aspects of these two bones. To acquire coronal images, the patient is positioned prone with the arm extended above the head, the elbow flexed 90^{o}, and with the medial side of the hand down (**Figure 39**).

Multislice CT scanners have a significant advantage over single-slice scanners in that only one position is necessary for acquiring the data, which can then be reformatted in any plane. On all machines, the patient is positioned head first and prone, with the affected arm extended above the head. For a multislice machine, the palm faces up (**Figure 39**).

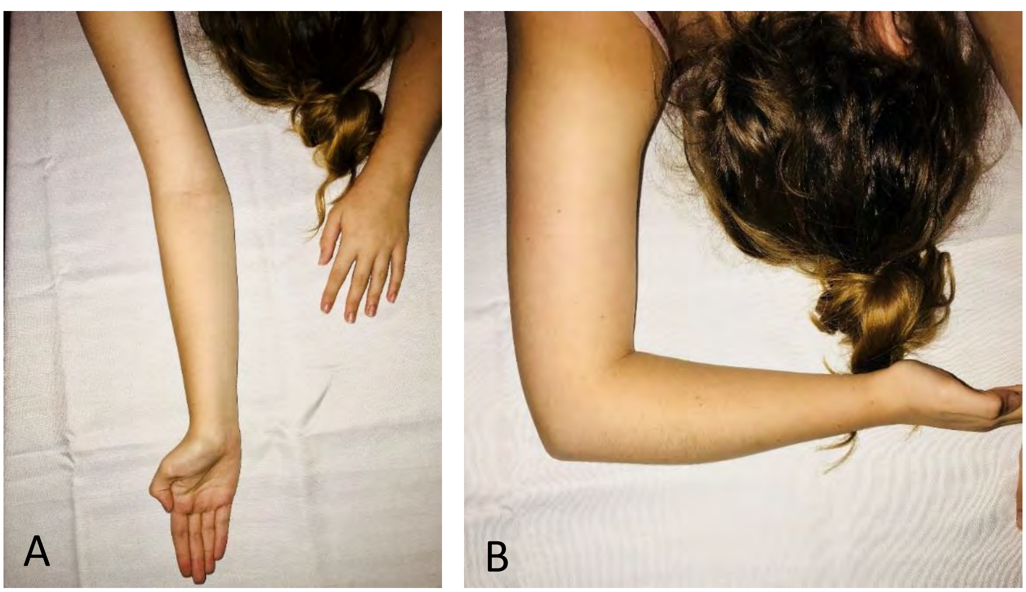

Figure 39. Elbow positioning for multi-slice scanning. (A) Patient is in the head-first, prone position, with the chin tucked in toward the trunk. The arm is extended in the supine position with the palm facing up. (B) Alternative position for patients who are unable to extend the arm. Patient is in the head-first, prone position with the chin tucked toward the trunk. The arm is over the head with the elbow flexed at 90° and the hand in the lateral position. Note: Positioning for single-slice scanning: Axial images of the elbow, the palm is down with the arm extended. Coronal images of the elbow, the arm is flexed at 90°.

If the patient is unable to lie on their stomach, they should be positioned supine, head first, with the affected arm raised above the head. Supports should be placed under the arm and the arm restrained to decrease motion.

If the affected arm cannot be raised, place the patient supine, feet first, and keep the affected arm at the patient's side in the AP position, palm facing up. Patients with broad shoulders may need to be offset to better center the area of interest in the gantry.

For CT scanning of the forearm, if the patient cannot lie prone then position supine, head first, with the affected arm above the head. Place supports under the arm and restrain to decrease motion. If the patient cannot raise the affected arm, place the patient feet first, supine, and keep the affected arm at the patient's side.

Thin, ≤1.25mm axial images should be obtained or reconstructed for fine bony detail and to reconstruct into coronal and sagittal planes. Scans should be acquired with the thinnest detector configuration, and the DFOV must be large enough (approximately 14cm) to include the entire surrounding soft tissue.

CT scanning is also used for diagnosing fractures, lesions, and abscesses in the humerus and forearm. **Figure 40** shows anatomical landmarks in the axial and coronal views.

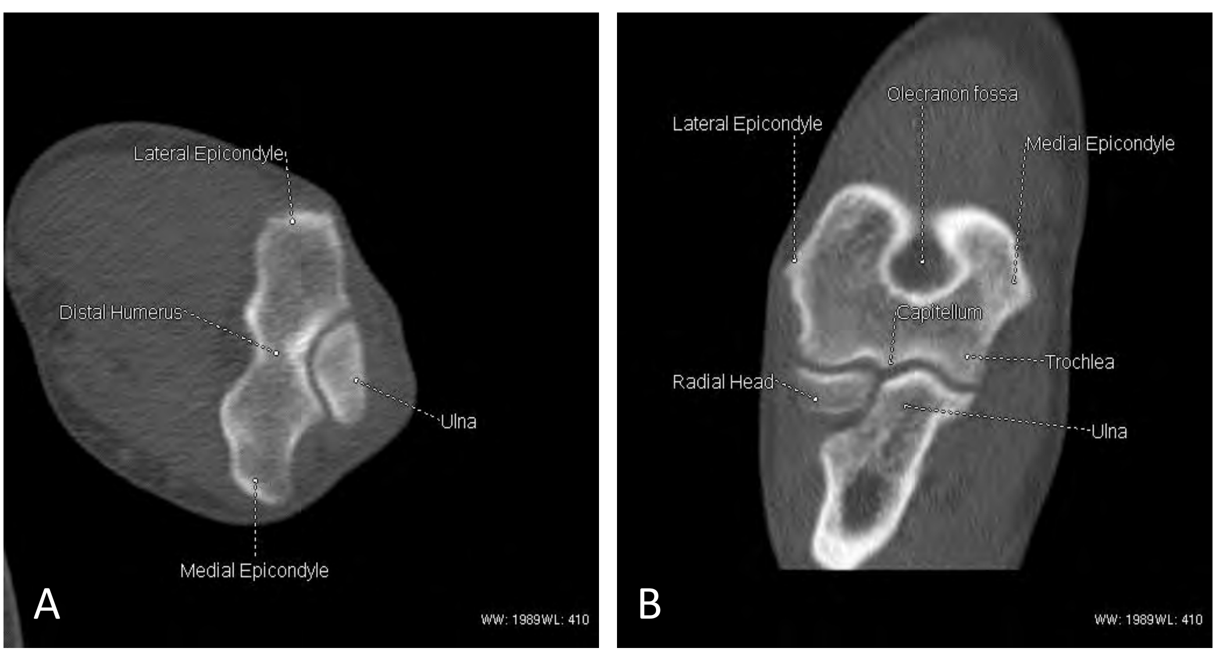

Figure 40. (A) Axial image of the elbow joint. (B) Coronal MPR of the elbow joint.

Multiplanar Reconstructions of the Elbow

Proper elbow reconstructions are more complicated than most, especially on patients who have just suffered elbow trauma or are experiencing pain. MPRs are easier to obtain on patients who can fully extend the elbow joint (a rare occurrence for someone with elbow pain). Below are examples of MPRs of a patient imaged with the elbow joint flexed.

For multiplanar reconstructions of the elbow:

- On an axial image, identify the inter-epicondyle line of the humerus (**Figure 41**).
- Obtain a plane parallel to the inter-epicondyle line to create coronal MPRs of the elbow (**Figure 42**).
- Obtain a plane perpendicular to the inter-epicondyle line to create sagittal MPRs of the elbow (**Figure 43**).
- Use a sagittal reference image to reconstruct the remaining elbow MPRs (**Figure 44**).
- Obtain a plane perpendicular to the humerus to create axial MPRs of the humerus (**Figure 45**).
- Obtain a plane parallel to the ulna to create coronal MPRs of the ulna (**Figure 46**).
- Obtain a plane parallel to the radius to create coronal MPRs of the radius (**Figure 47**).

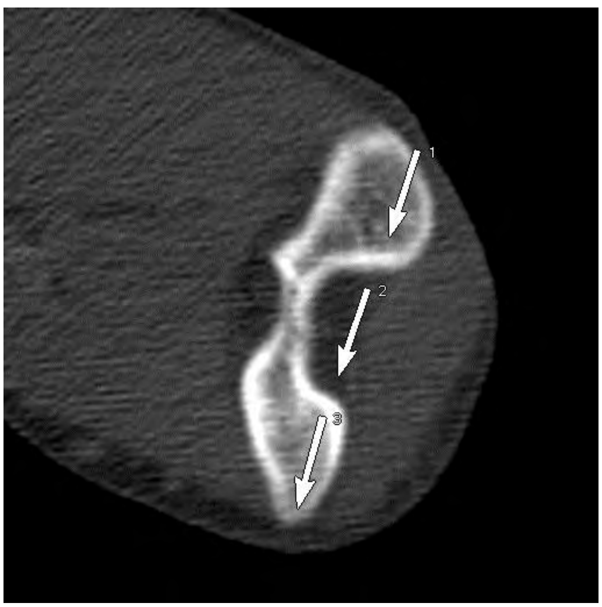

Figure 41. On the axial image of the elbow, identify the inter-epicondyle line of the humerus.

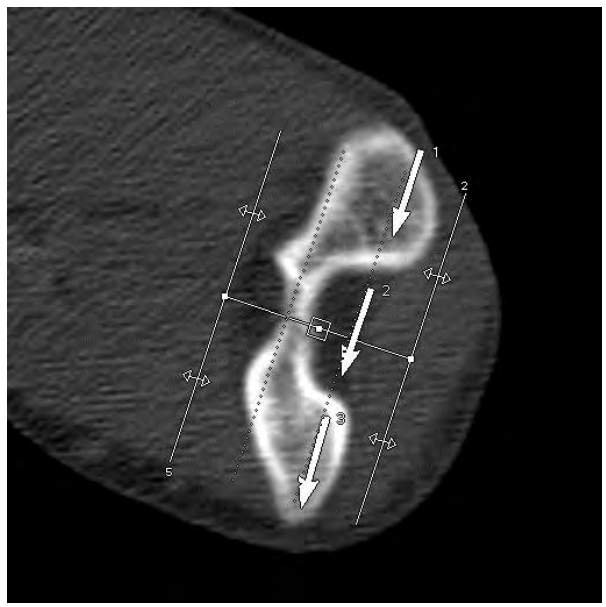

Figure 42. Obtain a plane parallel to the inter-epicondyle line to create coronal MPRs of the elbow.

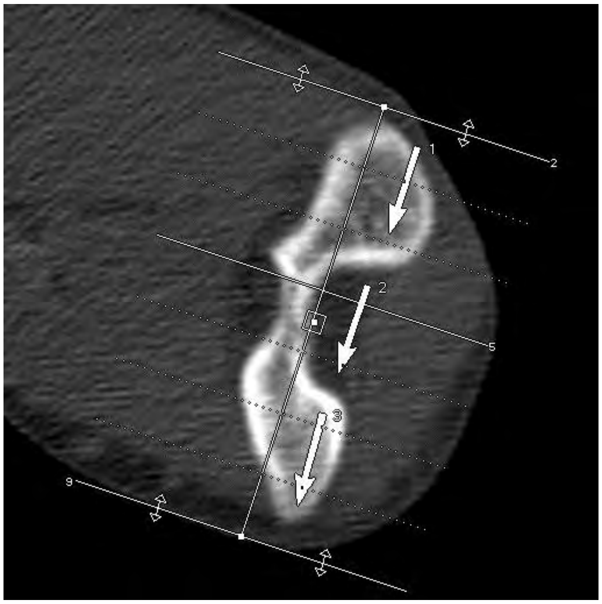

Figure 43. Obtain a plane perpendicular to the inter-epicondyle line to create sagittal MPRs of the elbow.

Figure 44. Use a sagittal reference image to reconstruct the remaining elbow MPRs.

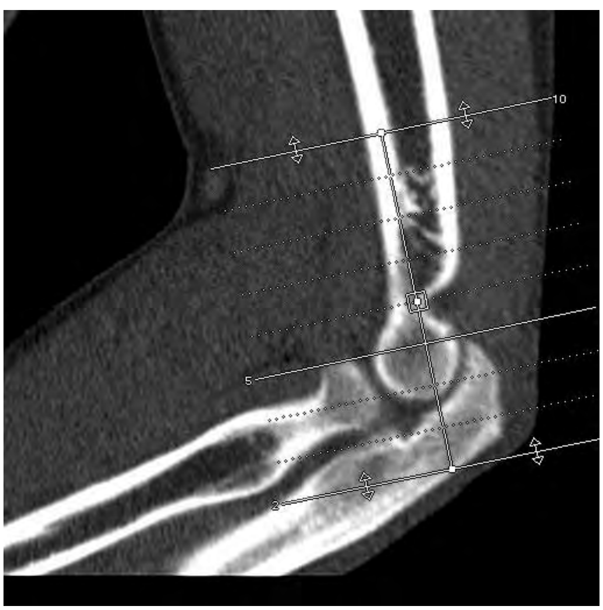

Figure 45. Obtain a plane perpendicular to the humerus to create axial MPRs of the humerus.

Figure 46. Obtain a plane parallel to the ulna to create coronal MPRs of the ulna.

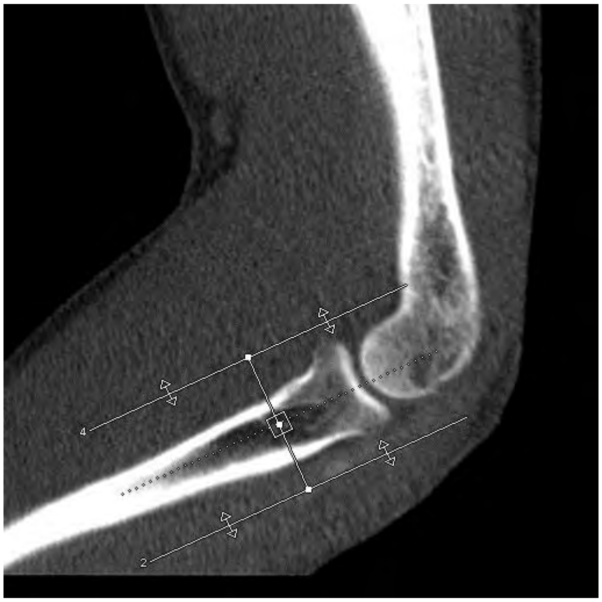

Figure 47. Obtain a plane parallel to the radius to create coronal MPRs of the radius.

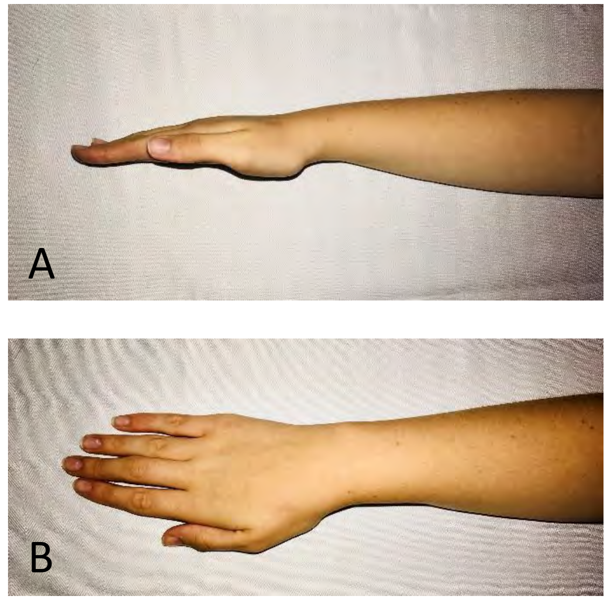

Figure 48. Positioning for CTs of the hand and wrist. (A) Patient is in the head-first prone position. The arm is extended overhead in a lateral or “karate chop” position. (B) Alternative position: Patient is in the head-first prone position. The arm is extended with the hand pronated, so that the hand is flat on the table.

CT SCANNING OF THE WRIST AND HAND

As with CT scanning of the elbow, CT scanning of the wrist and hand is indicated in cases of fracture when plain X-rays are inconclusive, and for delineation of complex fractures. 2D MPR or 3D VR images created from the acquired slices display the relationships among the fracture fragments; the wrist and hand can be evaluated from any perspective using this technique. CT scanning is less useful in the evaluation of carpal tunnel syndrome and ligamentous injuries, and MRI is most commonly used in such cases.

For CTs of the hand and wrist, the patient is positioned prone and head first, with the arm extended overhead in a lateral or “karate chop” position or, alternatively, in the prone position with the palm facing down. (**Figure 48**). Direct sagittal images are obtained with the arm extended over the head, the elbow flexed at 45^{o}, and the palmar surface of the hand down. Direct coronal images are obtained with the arm extended overhead and the elbow flexed 90^{o}, medial side down. The DFOV should encompass the minimal area necessary to demonstrate the pathology and affected surrounding tissues; the technologist should attempt to utilize a DFOV of 10cm. When using multidetector-row CT (MDCT) to image delicate structures such as the wrist and hand, the highest resolution is required, achieved by utilizing the narrowest detector configuration and acquiring or reconstructing thin slices of 1.25mm or less.

When using MDCT, the patient is scanned prone and head first with the arm extended and the wrist positioned lateral with the thumb up. Alternatively, the patient can position the palm down on the CT table.

Multiplanar Reconstructions of the Hand and Wrist

The MPR planes for the hands and the wrist are the same, with the exception of the fingers or the thumb, which require orthogonal coronal and sagittal reconstructions.

- Use a reference sagittal image to create coronal MPRs (**Figure 49**).
- Use a reference coronal image to create sagittal MPRs (**Figure 50**).
- Use a reference coronal image to create true axial MPRs (**Figure 51**).
- For navicular (scaphoid) fractures, use a reference coronal image to create images parallel to the navicular axis (**Figure 52**).

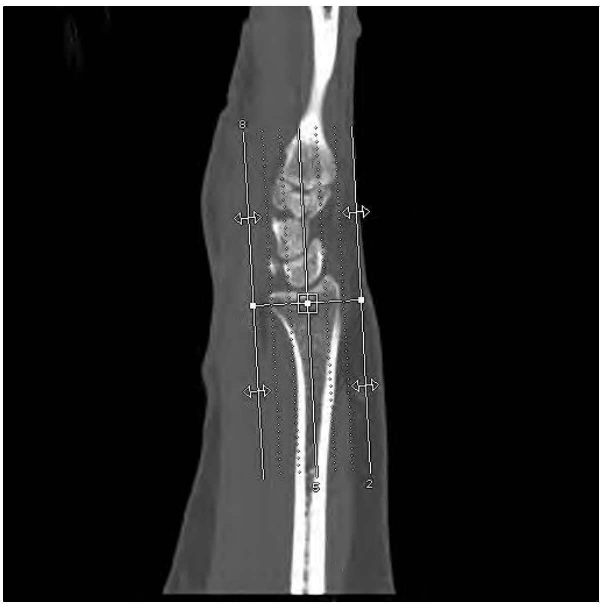

Figure 49. Use a reference sagittal image to create the coronal MPR of the wrist.

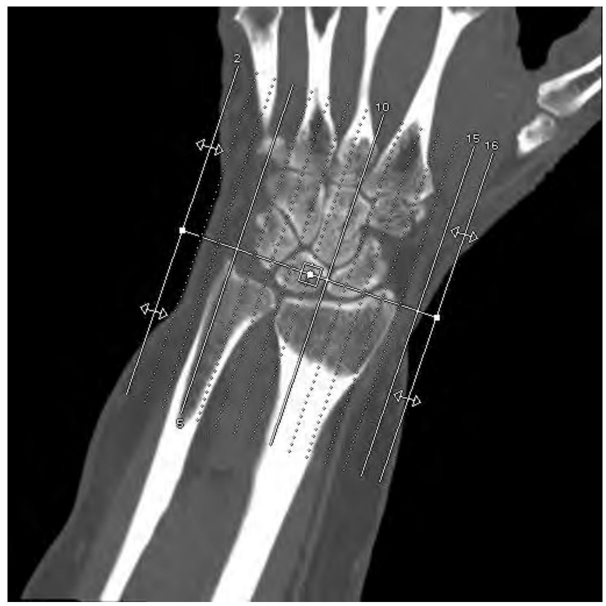

Figure 50. Use a reference coronal image to create sagittal MPRs of the wrist.

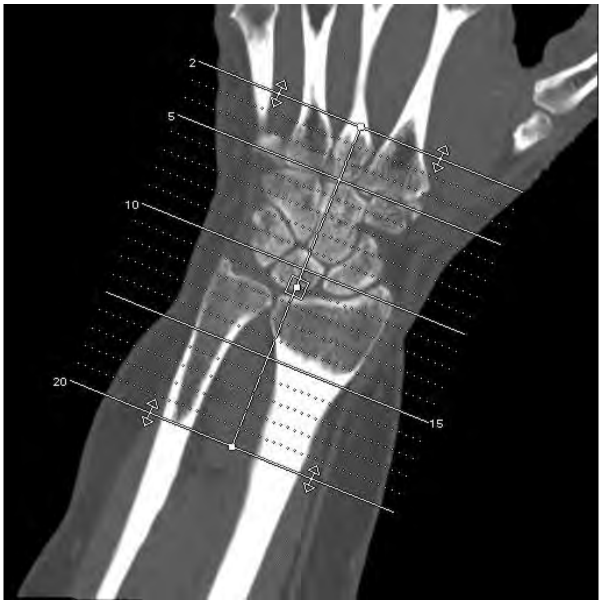

Figure 51. Use a reference coronal image to create true axial MPRs of the wrist.

Figure 52. For navicular (scaphoid) fractures, use a reference coronal image to create images parallel to the navicular axis.

CT SCANNING OF THE HIP AND PELVIS

There are many specific indications for CT of the hip and pelvis. Trauma is the most common; others include hip pain from tumors or arthritis, and infection. CT scanning is also used to evaluate subchondral or cortical fractures. One of the most frequently requested examinations is for the assessment of avascular necrosis (AVN). The femoral head receives its blood supply from a single end artery; if the blood flow in this vessel is disrupted by trauma or by certain disease processes leading to arterial emboli (such as sickle cell anemia), the loss of blood supply can lead to death of the tissue in the femoral head. Such tissue death can result in an abnormally shaped femoral head, degenerative disease, and arthritis.

For both hip and pelvis scanning, the patient is positioned feet first and supine into the scanner, with the legs internally rotated. The knees or feet should be taped together to prevent movement. The AP localizer scan should start above the iliac crest and extend to just below the lesser trochanter. Thin acquisition or reconstructed images of ≤1.25mm should be acquired for bony detail and to use for MPRs. If only one hip is being evaluated, the DFOV should be 20cm; if both hips are being evaluated, the DFOV should be large enough to include the pelvis.

Multidetector-row CT scanners facilitate the production of 2D MPR and/or 3D VR images that allow the hip to be viewed from any perspective, which is very helpful in cases of complex injuries. Any view (coronal/sagittal/oblique MPR/3D VR) may be created from the retrospectively reconstructed thin axial data set. Sophisticated software programs allow individual bones to be isolated and examined without overlap. Administration of IV contrast allows mapping of the iliac and femoral vessels, particularly useful in patients being evaluated for significant trauma to the area.

Contrast is also used to opacify soft tissue masses, metastases, or neoplasms; however, the determination of need for IV contrast should be made by a radiologist for each case.

Figure 53 shows the anatomical details of the hip in axial and coronal views.

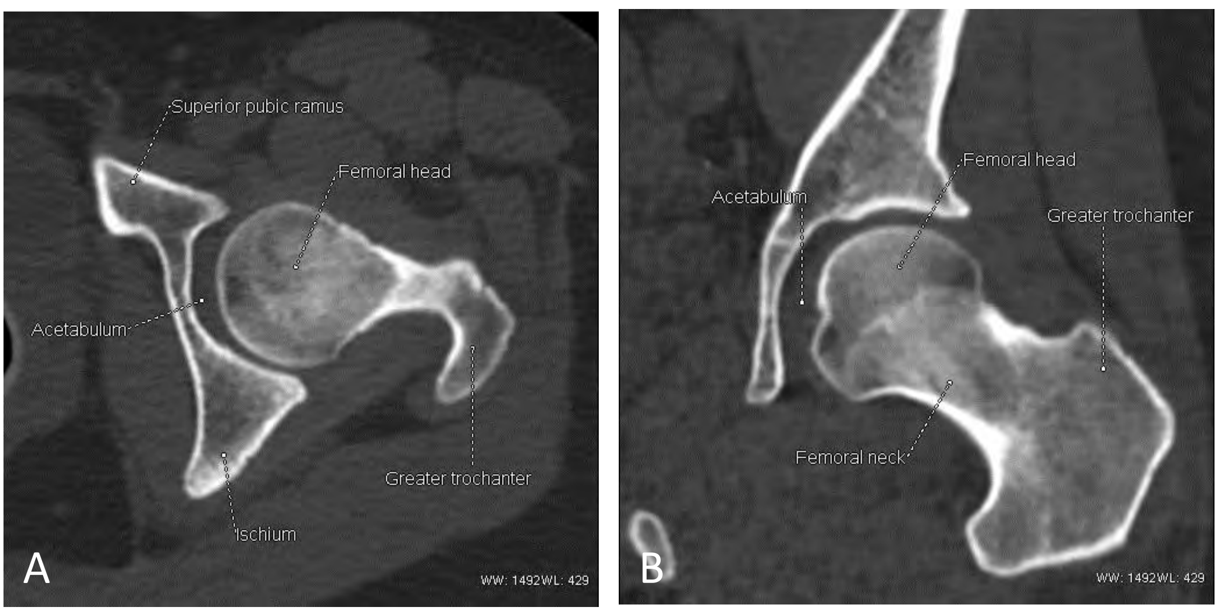

Figure 53. (A) Axial and (B) coronal images of the hip joint.

Multiplanar Reconstructions of the Hip

- On a reference axial image, identify the greater trochanter, femoral neck, and femoral head. Create a plane that bisects all three structures. This is the axis of the femoral head and neck **(Figure 54**).
- Obtain a plane parallel to the axis of the femoral head and neck to create coronal MPRs (**Figure 55**).
- Obtain a plane perpendicular to the axis of the femoral head and neck to create sagittal MPRs (**Figure 56**).
- Use a reference coronal view and obtain axial oblique images of the femoral neck that are parallel to the axis of the femoral head and neck (**Figure 57**).

Figure 54. On a reference axial image, identify the greater trochanter, femoral neck, and femoral head. Create a plane that bisects all three structures. This is the axis of the femoral head and neck.

Figure 55. Obtain a plane parallel to the axis of the femoral head and neck to create coronal MPRs of the hip.

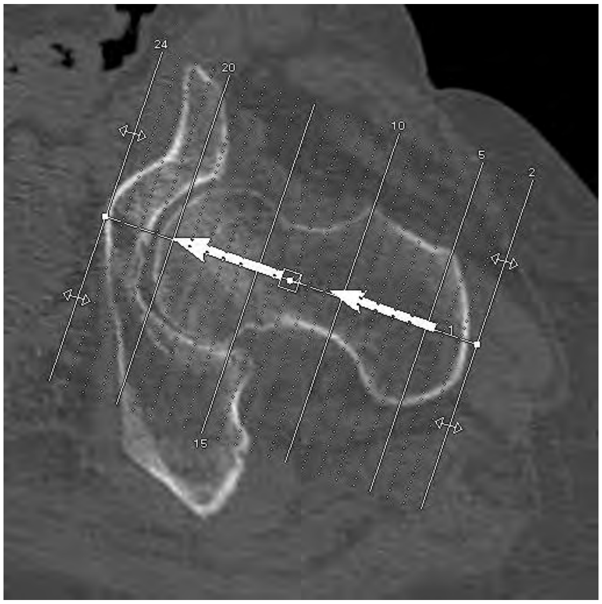

Figure 56. Obtain a plane perpendicular to the axis of the femoral head and neck to create sagittal MPRs of the hip.

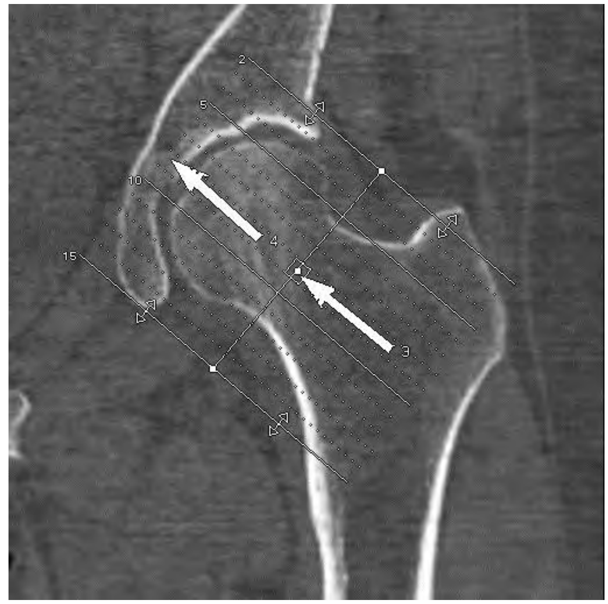

Figure 57. Use a reference coronal view and obtain axial oblique images of the femoral neck that are parallel to the axis of the femoral head and neck.

Multiplanar Reconstructions of the Pelvis

- Identify the anterior iliac line on a reference axial image (**Figure 58**).
- Obtain a plane parallel to the anterior iliac line to create coronal MPRs (**Figure 59**).
- Obtain a plane perpendicular to the anterior iliac line to create sagittal MPRs (**Figure 60**).
- True axial images obtained on a coronal reference image (**Figure 61**).

Figure 58. Identify the anterior iliac line on a reference axial image of the pelvis.

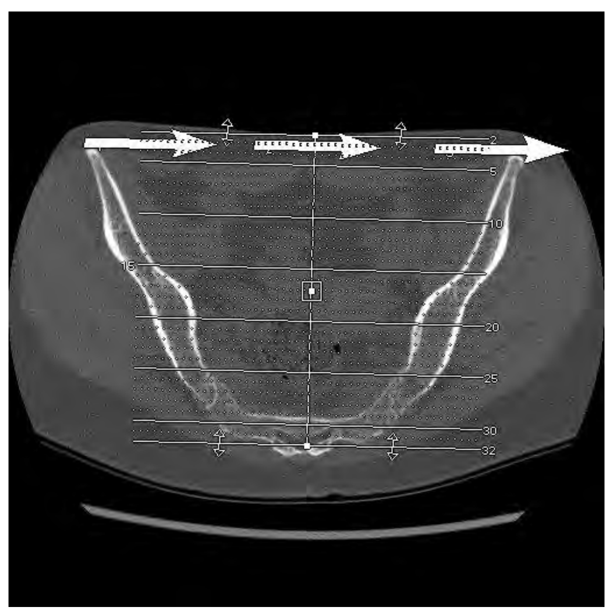

Figure 59. Obtain a plane parallel to the anterior iliac line to create coronal MPRs of the pelvis.

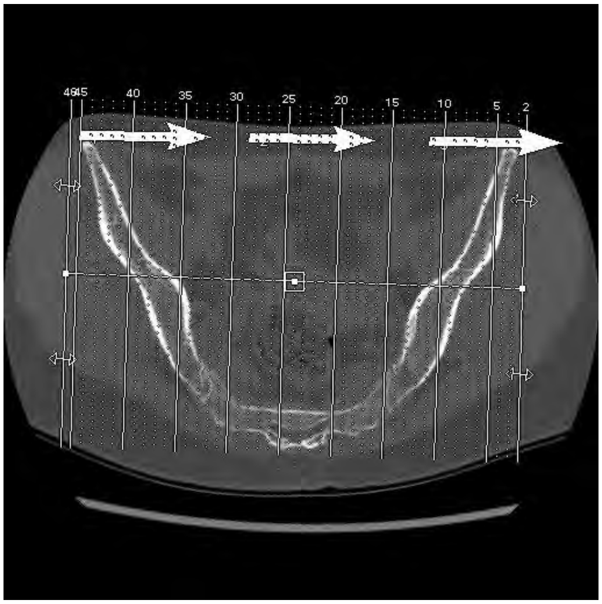

Figure 60. Obtain a plane perpendicular to the anterior iliac line to create sagittal MPRs of the pelvis.

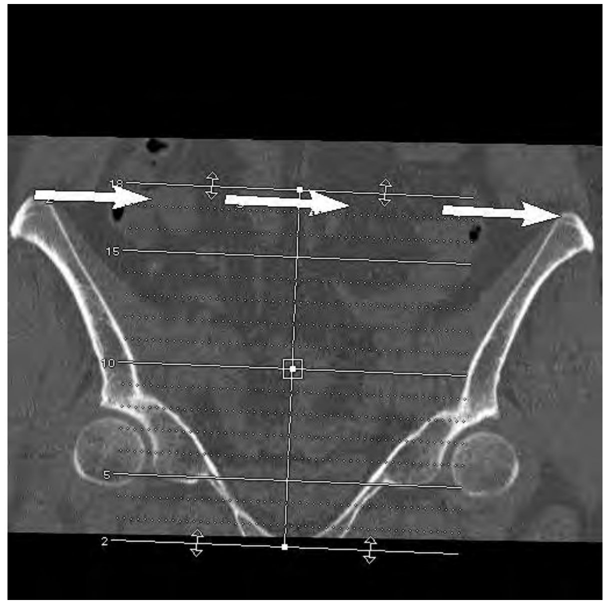

Figure 61. True axial images obtained on a coronal reference image.

CT SCANNING OF THE KNEE AND LOWER LEG

Imaging of the knee is often performed using MRI, the preferred method for evaluating the ligaments and menisci. Nevertheless, CT scanning with 2D MPR and 3D VR is ideal for a number of clinical indications, including assessment of tibial plateau fractures, patellofemoral disorders, damage to the articular cartilage, the presence of bony lesions, and for surgical planning.

The patient is positioned feet first and supine into the scanner, with the feet internally rotated. Thin sections of ≤1.25mm should be acquired or reconstructed for fine bony detail and to use for MPRs. If only one knee is being evaluated, the DFOV should be 15-18cm; if both knees are being evaluated, the DFOV should be large enough to include both knees (23-30cm). Many sites will retrospectively reconstruct each knee separately at a smaller DFOV to maximize image quality. CT scanning also provides valuable information in the evaluation of the distal femur, proximal tibia, and fibula.

Multiplanar Reconstructions of the Knee and Lower Leg

- On a reference axial, identify the posterior intercondylar line (**Figure 62**).
- Obtain coronal MPRs by reconstructing images parallel to the posterior intercondylar line (**Figure 63**).
- Obtain sagittal MPRs by reconstructing images perpendicular to the posterior intercondylar line (**Figure 64**).
- On a reference coronal image, create true axial MPRs of the tibia by reconstructing images parallel to the tibial plateaus (**Figure 65**).

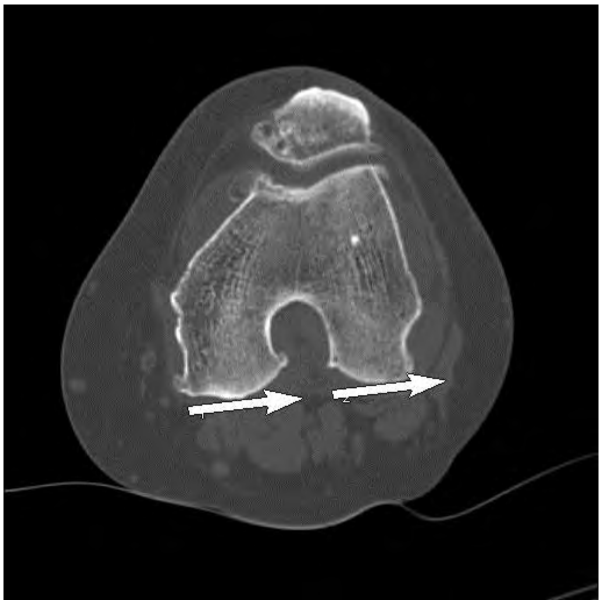

Figure 62. On reference axial image of the knee, identify the posterior intercondylar line.

Figure 63. Obtain coronal MPRs of the knee by reconstructing images parallel to the posterior intercondylar line.

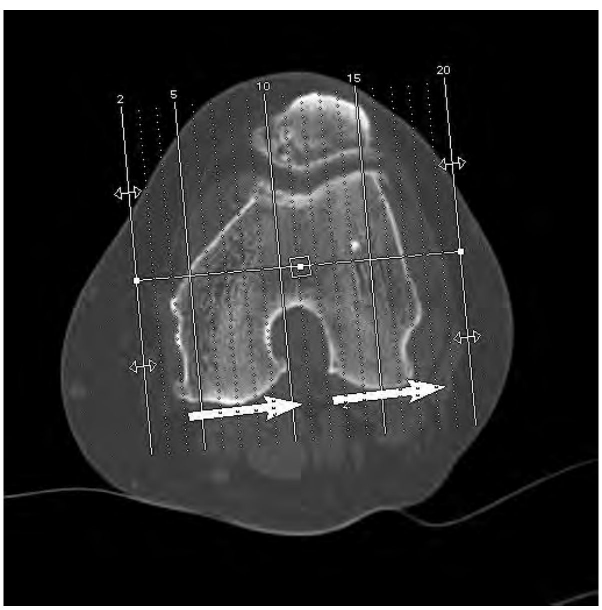

Figure 64. Obtain sagittal MPRs by reconstructing images perpendicular to the posterior intercondylar line.

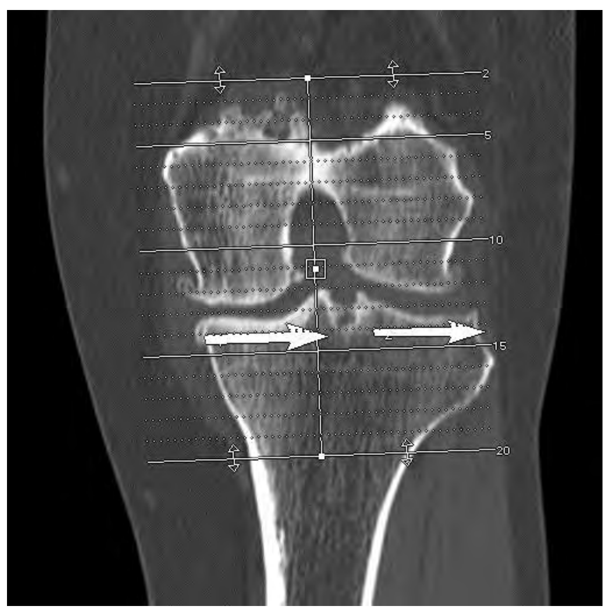

Figure 65. On a reference coronal image, create true axial MPRs of the tibia by reconstructing images parallel to the tibial plateaus.

CT SCANNING OF THE ANKLE AND FOOT

CT scanning of the ankle is used for the evaluation of complex trauma, especially when difficult surgery may be necessary. MDCT with 2D MPR or 3D VR provides limitless views of the relationships of the multiple bones that comprise the ankle mortices (**Figure 66**). CT scans are also used to assess the presence and extent of infection and to determine which compartments of the ankle are involved (subcutaneous tissue, fascia, muscle, or bone). Spiral CT is used to evaluate cortical bone and calcification in the soft tissues of the ankle.

The patient is placed feet first and supine into the scanner, with the knee of the affected ankle extended and the toes pointed up (**Figure 67**). Both ankles can be scanned together for comparison purposes; however, they must be positioned symmetrically. As with the knee, images from each ankle should be retrospectively reconstructed at the smallest possible DFOV.

Direct axial or coronal scans of the ankle may be obtained with a single-slice scanner. For direct axial scans, an anteroposterior localizer scan is used, while a lateral localizer scan is used to determine the correct cephalic gantry angle for direct coronal images. If direct coronal scans are being obtained, the patient's knees should be flexed, with the plantar surface of the foot placed flat on the table. For either scan, a slice thickness of 3mm is used; thinner slices are used to evaluate subtle bony erosions or small cortical avulsion fractures.

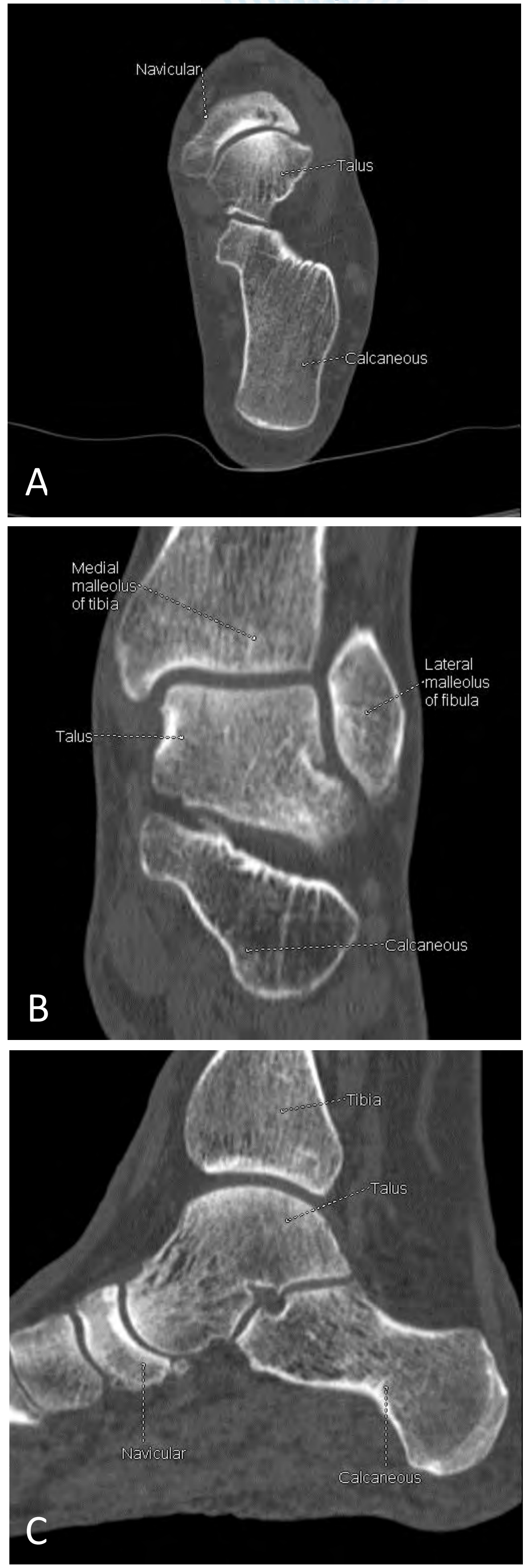

Figure 66. Ankle anatomy: (A) axial; (B) coronal and (C) sagittal images.

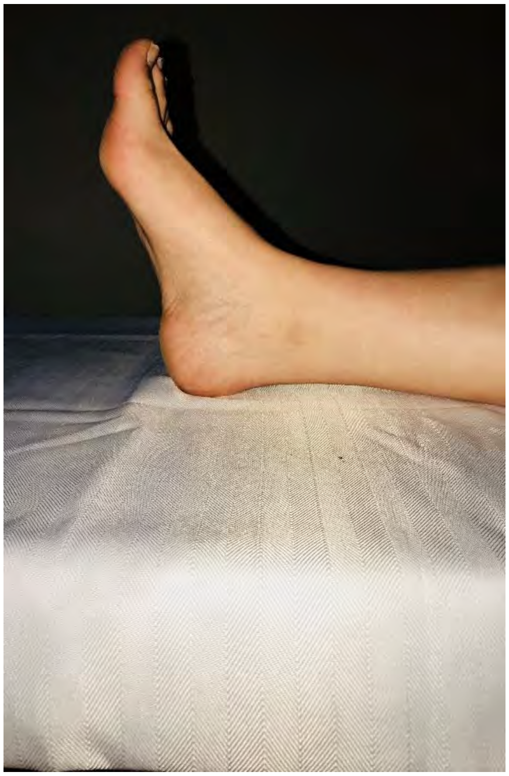

Figure 67. Correct positioning for axial imaging of the foot and ankle.

When performing MDCT, use of the narrowest detector configuration produces a data set of very near-isotropic voxels that can be manipulated on a workstation. The radiologist will often create these images in direct consultation with the orthopaedic surgeon.

Intravenous contrast aids in cases of suspected infection in muscle or soft tissue. Abnormal muscle typically enhances to a greater extent than normal muscle; therefore, maximum enhancement patterns should be employed to maximize lesion diagnosis and establish a differential diagnosis. Intravenous contrast is also standard for evaluation of the vasculature of the ankle.

CT scanning is used for the evaluation of injury and pathologic processes in the foot. As in the ankle, most CT scanning of the foot is performed to evaluate complex trauma and fractures (**Figure 68**).

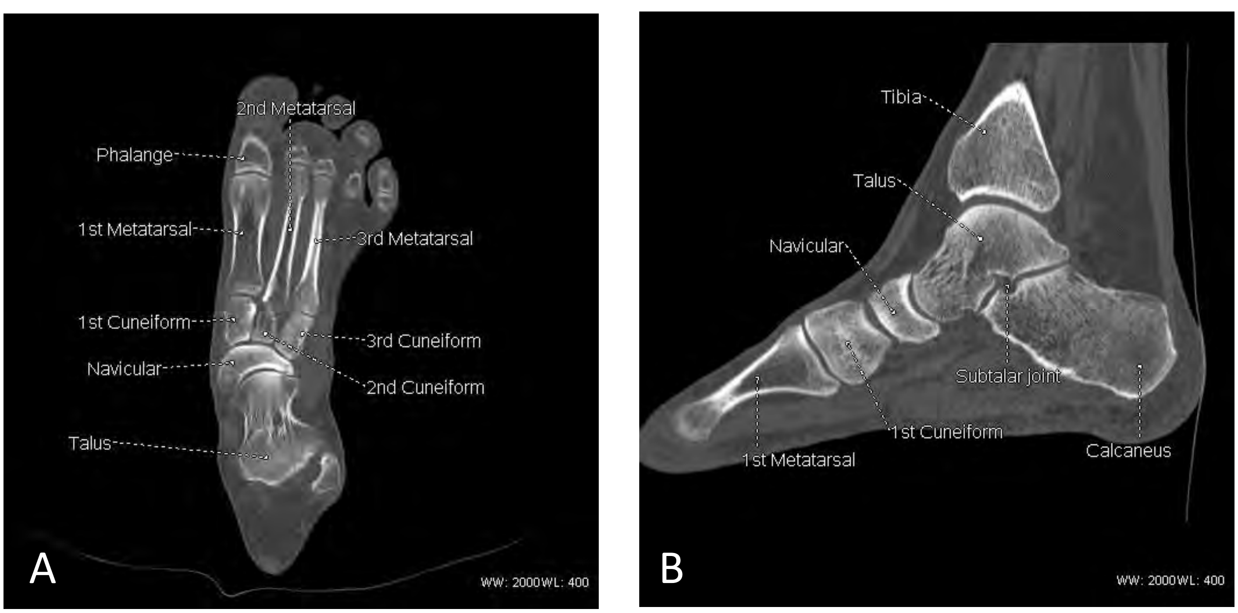

Figure 68. (A) Axial and (B) sagittal images of the medial aspect of the foot.

Multiplanar Reconstructions of the Ankle

- On a reference axial image, identify the lateral and medial malleoli line (**Figure 69**).
- To obtain coronal MPRs, reconstruct images parallel to the lateral and medial malleoli line (**Figure 70**).
- To obtain sagittal MPRs, reconstruct images perpendicular to the lateral and medial malleoli line (**Figure 71**).
- On a reference sagittal image, reconstruct true axial MPRs (**Figure 72**).

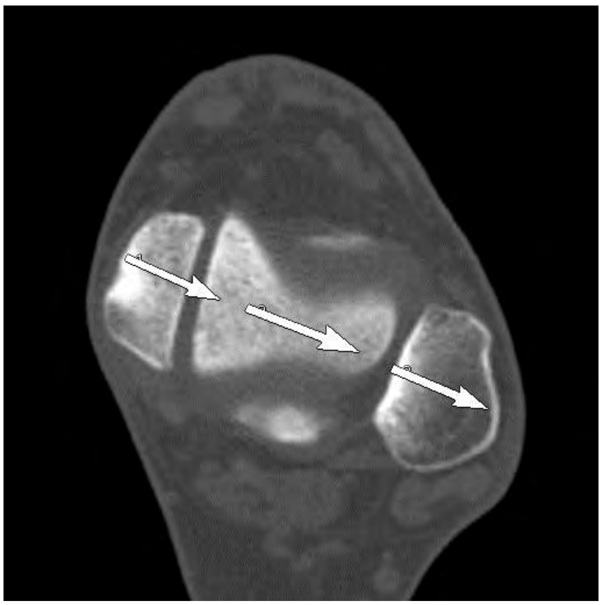

Figure 69. On a reference image, identify the lateral and medial malleoli line.

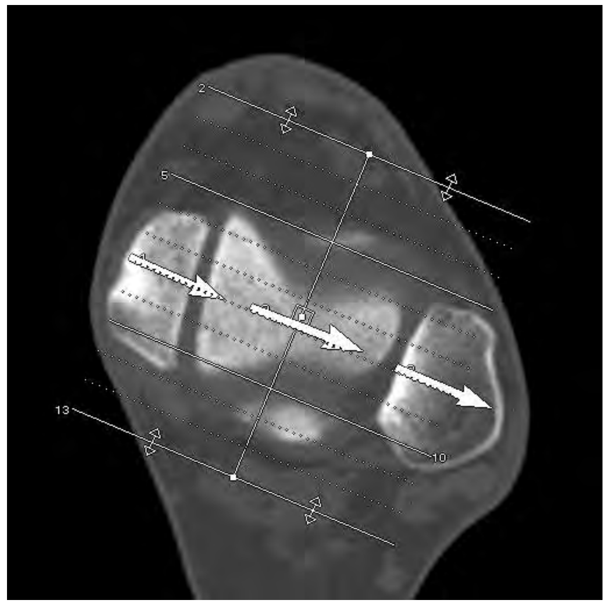

Figure 70. To obtain coronal MPRs, reconstruct images parallel to the lateral and medical malleoli line.

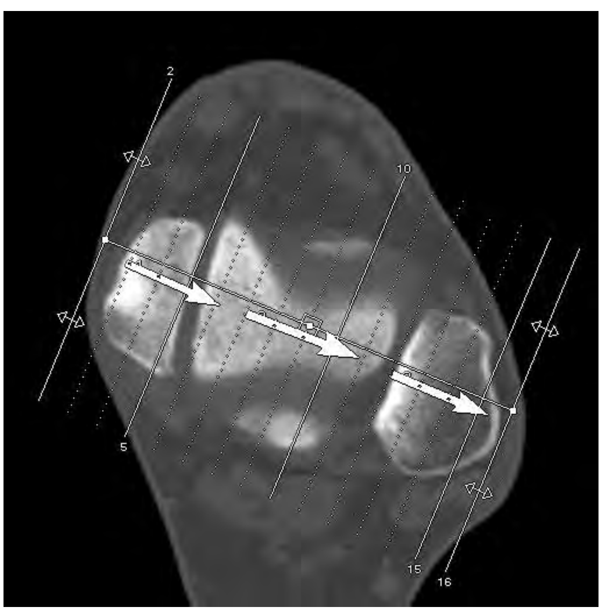

Figure 71. To obtain sagittal MPRs, reconstruct images perpendicular to the lateral and medial malleoli line.

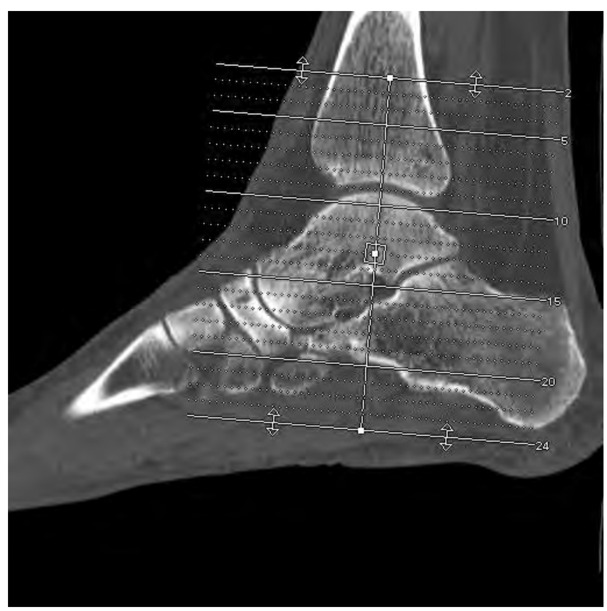

Figure 72. On a reference sagittal image, reconstruct true axial MPRs.

Multiplanar Reconstructions of the Foot

- Identify the Chopart joint on a reference axial image (**Figure 73**).
- Obtain sagittal MPRs by reconstructing images perpendicular to the Chopart joint line (**Figure 74**).
- Use a reference sagittal image to reconstruct true axial images (**Figure 75**).
- Identify the Chopart joint line on a reference sagittal image (**Figure 76**).
- Obtain axial oblique images by reconstructing in a plane perpendicular to the Chopart joint line (**Figure 77**).
- Obtain coronal images using a reference sagittal image (**Figure 78**).
- On a reference sagittal image, identify the posterior subtalar joint. Obtain coronal oblique images of the calcaneus by reconstructing images perpendicular to the posterior subtalar joint (**Figure 79**).

Figure 73. Identify the Chopart joint on a reference axial image.

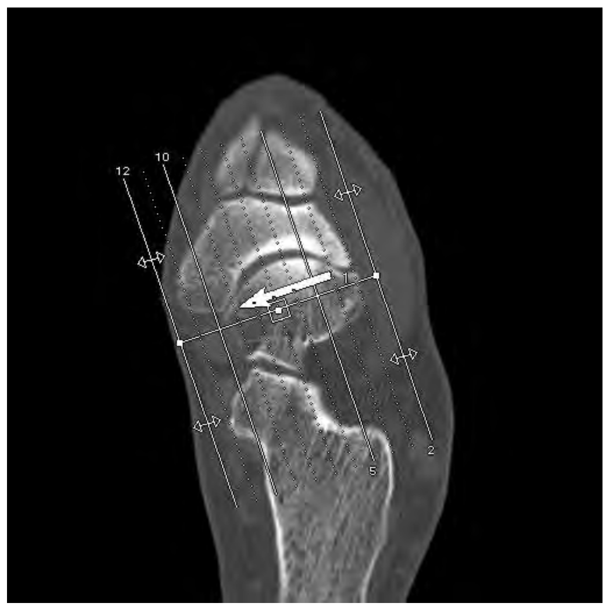

Figure 74. Obtain sagittal MPRs by reconstructing images perpendicular to the Chopart joint line.

Figure 75. Use a reference sagittal image to reconstruct true axial images.

Figure 76. Identify the Chopart joint line on a reference sagittal image.

Figure 77. Obtain axial oblique images by reconstructing in a plane perpendicular to the Chopart joint line.

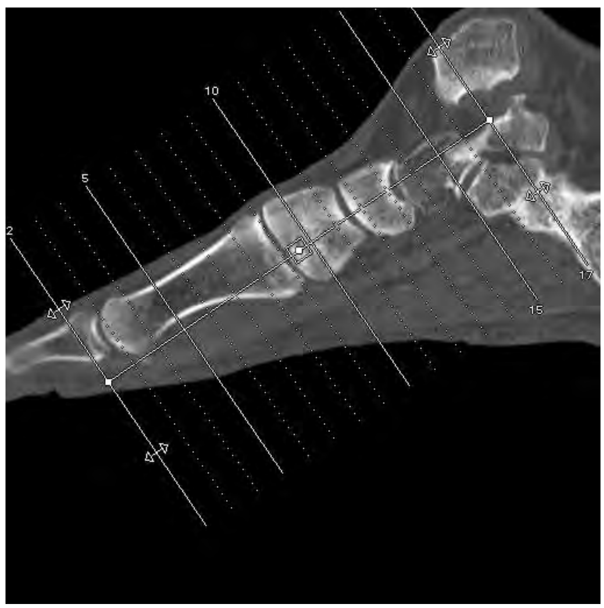

Figure 78. Obtain coronal images using a reference sagittal image.

Figure 79. On a reference sagittal image, identify the posterior subtalar joint. Obtain coronal oblique images of the calcaneus by reconstructing images perpendicular to the posterior subtalar joint.

Figure 80. Axial image of pelvis shows bilateral hip replacement with streak artifacts and beam hardening effect.

MSK PRE-SURGICAL PLANNING EXAMS

Prior to orthopaedic surgery, patients will often require a CT scan for surgical planning for implantation of a specific orthopaedic device. The images are usually sent to a lab affiliated with the manufacturer of the particular surgical device. Surgical planning protocols must be followed precisely to avoid unnecessary patient call-backs. Surgical implants of the shoulder, hip, knee, and ankle are most common. Images can be sent to the lab electronically via a secure server (**Figures 80, 81, and 82**).

Figure 81. Coronal image of pelvis shows bilateral hip replacement.

Figure 82. 3D volume-rendered image of pelvis of patient with bilateral hip replacements.

MULTI-OBLIQUE RECONSTRUCTIONS

CT MSK scans not properly aligned due to poor positioning may require multi-oblique reconstructions before reconstructing sagittal and coronal MPRs. The example below shows a humerus that was not in a proper coronal plane due to a poorly positioned elbow joint. Because the patient’s hand was not supinated before the generation of sagittal reconstructions, multi-oblique reconstructions had to be obtained.

- Three imaging planes of the humerus in a suboptimal position (**Figure 83**).
- Coronal image of poorly positioned humerus. Note reconstruction plane is not orthogonal to humerus (**Figure 84**).
- Proper adjustment of the image plane parallel to the humerus (**Figure 85**).
- Axial image of poorly rotated elbow joint. This must be adjusted to create a coronal image of the humerus (**Figure 86**).
- The reconstruction plane is rotated to bisect the medial and lateral epicondyles of the humerus (**Figure 87**).
- The resulting coronal image after multi-oblique reconstructions (**Figure 88**).
- Proper plane for orthogonal sagittal MPRs parallel to the coronal humerus image (**Figure 89**).

Figure 83. Three imaging planes of the humerus in a suboptimal position.

Figure 84. Coronal image of poorly positioned humerus. Note reconstruction plane is not orthogonal to humerus.

Figure 85. Proper adjustment of the image plane parallel to the humerus.

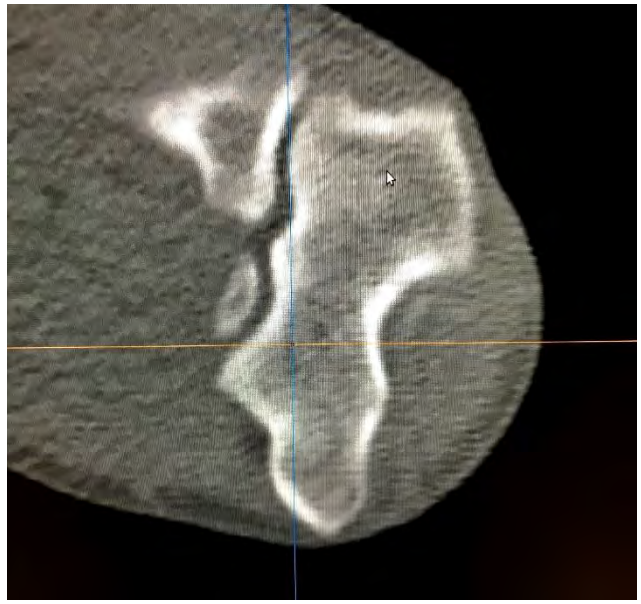

Figure 86. Axial image of poorly rotated elbow joint. This must be adjusted to create a coronal image of the humerus.

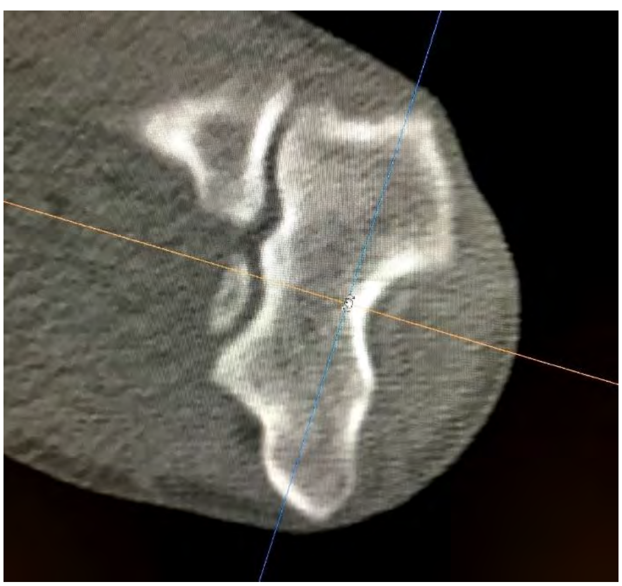

Figure 87. The reconstruction plane is rotated to bisect the medial and lateral epicondyles of the humerus.

Figure 88. The resulting coronal image after multi-oblique reconstructions.

Figure 89. Proper plane for orthogonal sagittal MPRs parallel to the coronal humerus image.

Figure 90. 3D volume-rendered movie of the pelvis.

To view the movie click HERE

3D IMAGING OF THE EXTREMITIES

Volume-rendered 3D images have many applications in MSK CT. Complicated fractures can be visualized in a manner that is easier to process than viewing multiple stacked images in different image planes. Orthopaedic surgeons may also find it beneficial to explain non-subtle findings to a patient on a 3D model rather than on an axial CT image. 3D software allows the user to remove structures to help visualize pathology, once again making it easier to understand.

Creating 3D images of bone is rather simple for an experienced user (**Figure 90**). The best quality 3D images are generated using thin section axial images, preferably ≤1mm. Thin images using a bone filter may create a 3D model with increased artifact due to image noise. In those instances, thin images with a soft tissue algorithm may be used but may create an overly smooth model that does not demonstrate subtle detail. The user can create screen shots or movies of the 3D model, which can also be a useful teaching tool.

SUMMARY

Computed tomography is the imaging modality of choice for a number of indications involving the upper and lower extremities. With 2D MPR and 3D VR techniques, images can be rendered in any plane. The technologist must take care to precisely reconstruct images in the required planes for the extremity or joint being imaged. High-quality images may even be acquired through a patient's external cast. CT is indispensable for determining the location of bone fragments following small fractures and for the assessment of other complex bone and cartilage injuries. The addition of intravenous iodinated contrast is essential for evaluating the vasculature of the major musculoskeletal joints, as well as for the detection of tumors and metastases.

C H A P T E R T H R E E

CT Examination of the Spine

After completing this section, the reader will be able to:

- Identify the important anatomic landmarks of the cervical, thoracic, lumbar, and sacral spine
- Describe the primary indications for CT scanning of the cervical, thoracic, lumbar, and sacral spine
- Apply appropriate protocols for optimized CT imaging

INTRODUCTION

The highly complex anatomy of the spine serves two basic functions: a *neurologic* function performed by the spinal cord and its membranous cover, and a *structural* function performed by the vertebral bodies. The primary functions of the spinal column are to provide attachment sites for muscles necessary for erect posture; to support the ribs, which makes breathing possible; and to protect the spinal cord. The spine is vulnerable to a number of highly significant, frequently encountered disease states and injuries, including traumatic injury, compression fractures due to osteoporosis, radiculopathy, spondylolisthesis, metastatic carcinoma, and degenerative disc disease.

This chapter reviews the normal anatomy of the spine and its associated tissues and offers protocols for CT scans of the four major anatomic regions of interest: the cervical region, the thoracic region, the lumbar region, and the sacrum and coccyx.

ANATOMY OF THE SPINE

The structural element of the spinal column is composed of 24 vertebral bodies: 7 cervical, 12 thoracic, and 5 lumbar (**Figure 91**). The upper cervical vertebrae have specialized attachments to the base of the skull, while the lower lumbar vertebral bodies—specifically the fifth lumbar—articulate with the sacrum. The vertebral bodies of the spine serve to support the individual's body weight, maintain upright posture, and protect the spinal cord and nerve roots. When viewed from the side in a lateral projection, the spinal column is not straight but rather has four gentle curves: the cervical and lumbar spines curve anteriorly—lordotic—and the thoracic spine and sacrum curve posteriorly—kyphotic. When viewed from the front or back, the spinal column is a straight line; any lateral curvature is called scoliotic or having scoliosis (**Figure 92**).

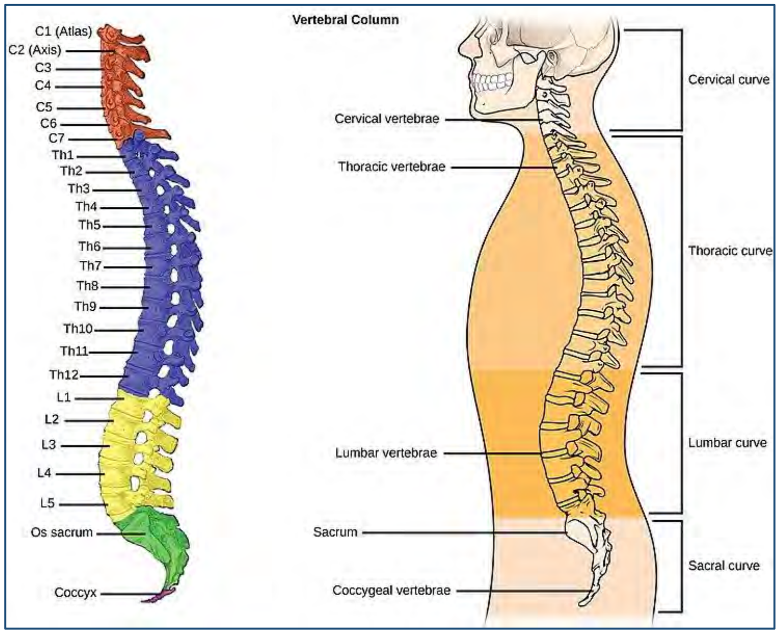

Figure 91. Illustration of spinal vertebra and position in the body.
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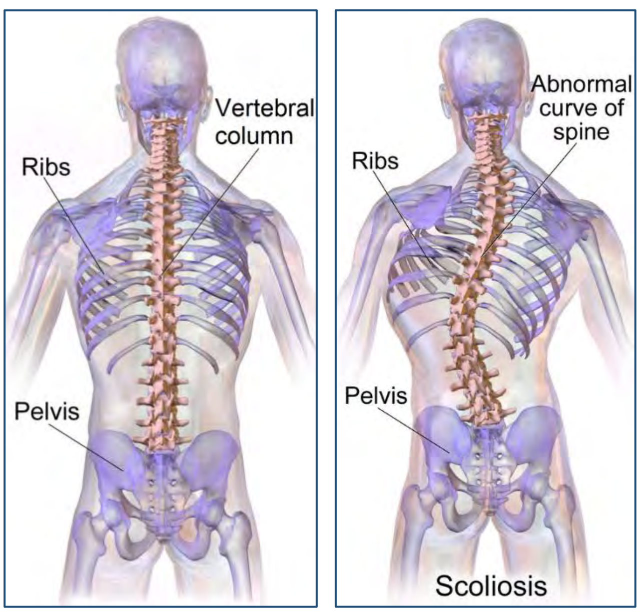

Figure 92. LEFT: Illustration of normal vertebral column.
Available at commons.wikimedia.org

RIGHT: Illustration of scoliosis, a lateral curvature of the spine. Available at commons.wikimedia.org

The Vertebral Bodies

The vertebrae vary considerably in size and shape. Regardless of their location, each vertebral body has three similar components: the body, the posterior elements, and the transverse processes. Each of these basic structural elements is modified at each level of the spine to perform specific functions. The vertebral bodies are roughly cylindrical in shape, with

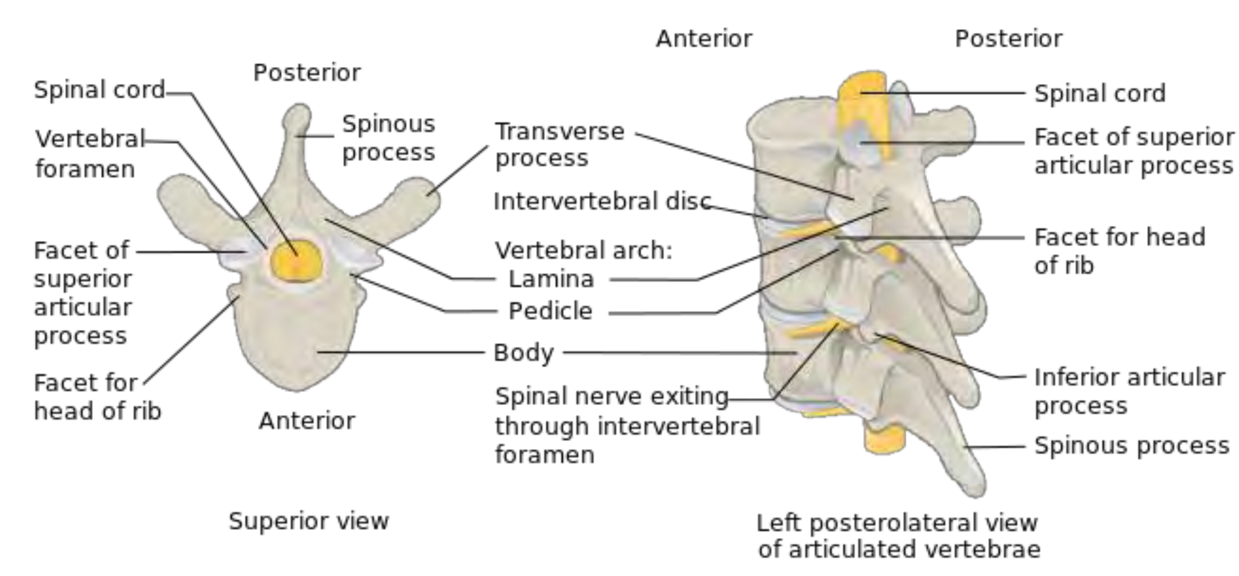

Figure 93. Illustration of vertebral anatomy. Available at [commons.wikimedia.org]

end plates comprised of compact bone on the superior and inferior surfaces (**Figure 93**). Each vertebral body is separated from the adjacent body by a disc. Discs are named by the interspace at which they are found; for example, an L4-5 disc is found between the fourth and fifth lumbar vertebral bodies. Understanding this nomenclature is important as CT scans are often ordered to assess specific disc interspaces. The discs serve as shock absorbers for the spinal column. They are comprised of a soft, gelatinous central mass (the nucleus pulposus) and a fibrous outer ring (the annulus fibrosis). Together, the nucleus pulposus and the annulus fibrosis are generically referred to as "the disc" (**Figure 94**).

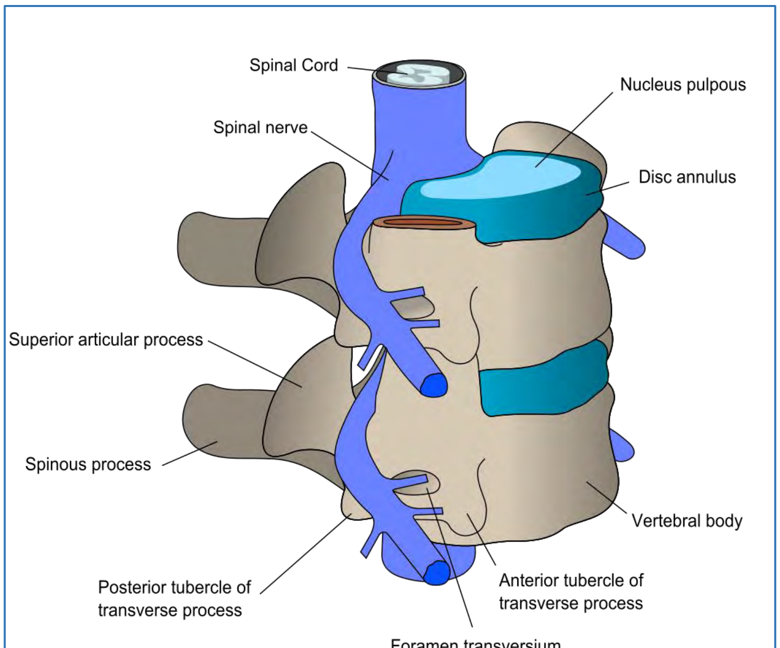

Figure 94. Illustration of cervical vertebra; note the vertebral disc, comprised of the nucleus pulposus and annulus. Available at [commons.wikimedia.org]

Posterior to each vertebral body is the vertebral foramen, through which runs the spinal cord, nerves, and blood vessels (**Figure 95**). The foramen is bordered anteriorly by the posterior portion of the vertebral body, laterally by two thick bony struts called the

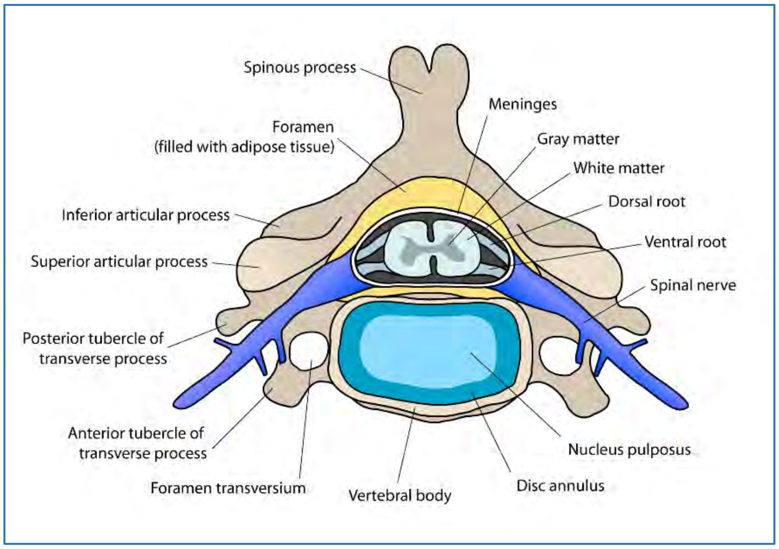

Figure 95. Illustration of a cervical vertebra; note the foramen, through which the spinal cord, nerves, and blood vessels run. Available at commons.wikimedia.org

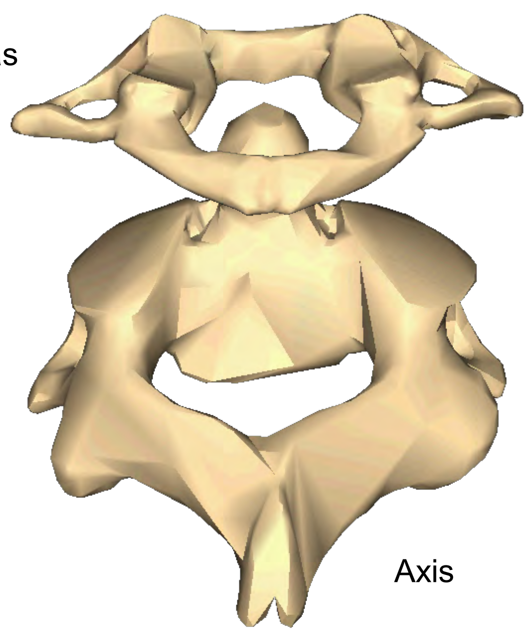

Figure 96. TOP: Illustration of C1, also called the atlas, which rests on C2. Available at commons.wikimedia.org

BOTTOM: Illustration of C2, also call the axis. Together, the atlas and axis form the joint that connects the head and spine. Available at commons.wikimedia.org

pedicles, and posteriorly by the lamina. The pedicles and lamina comprise the posterior elements. Several important protrusions extend from the posterior elements. Directly posterior to the lamina is the spinous process, and laterally are two transverse processes. Additionally, there are paired superior and inferior articulating processes that serve as the joints between the two adjacent vertebral bodies. The seven cervical vertebrae differ in shape and size from the thoracic and lumbar vertebrae, as well as from each other. The cervical vertebrae contain transverse foramina, which are contained in the transverse processes. These foramens allow passage of the vertebral arteries to the skull and protect them within a bony sheath. The C1 vertebra is called the atlas (**Figure 96**) and has large superior processes that articulate with the condyles on the basilar surface of the skull. The atlas is a ring-like structure that has no body or spinous processes; instead, it consists of an anterior and posterior arch with two large lateral masses.

Figure 97. Illustration of the anatomy of the cervical spine.
Available at commons.wikimedia.org

Figure 98. Illustration of the anatomy of the thoracic spine.
Available at commons.wikimedia.org

The C2 vertebra is also called the axis (**Figure 96**). This vertebra contains a unique process called the dens, an odontoid (tooth-like) process that extends upward from the superior surface of the vertebral body. The dens projects into the ring formed by the atlas, acting as a pivot for the rotational movement of the axis. The superior articular process of the axis also provides rotation of C1.

The anatomy of C3 through C6 is more similar to that of the thoracic and lumbar vertebrae, with the exception of a bifurcated spinous process. While the last cervical vertebra, C7, has a similar shape, its spinous process is long and not bifurcated. The spinous process of this vertebra (also called the vertebrae prominens) can be felt posteriorly at the base of the neck (**Figure 97**).

The 12 thoracic vertebrae are largely uniform in shape (**Figure 98**). The spinous processes of these vertebrae are long and slender and project inferiorly over the vertebral arches of the vertebra below. Superior and inferior costal facets on the vertebral bodies articulate with the ribs, forming the costovertebral joints, while the costotransverse joints are formed by the articulations between the ribs and transverse processes.

The five lumbar vertebrae, like the thoracic vertebrae, are similar in shape. These vertebrae increase in size from L1 to L5 in order to provide the primary support for the weight of the entire upper body, which is transferred from L5 to the sacrum (**Figure 99**).

Figure 99. Illustration of anatomy of the lumbar spine.
Available at commons.wikimedia.org

The sacrum is formed by the fusion of five vertebrae (S1-S5) directly below the lumbar vertebrae (**Figure 100**). Roughly triangular in shape, the sacrum extends backward and downward from the lumbar portion of the spine to form the posterior portion of the pelvis. The entire lateral margin of the sacrum forms a joint with the iliac wing on the same side. The sacroiliac joint, commonly called the SI joint, has an important role as it provides attachment of the vertebral column to the pelvis and lower extremities (**Figure 101**). The coccyx, commonly known as the tailbone, is the lowest part of the vertebral column and is attached by ligaments to the lower margins of the sacrum (**Figure 100**).

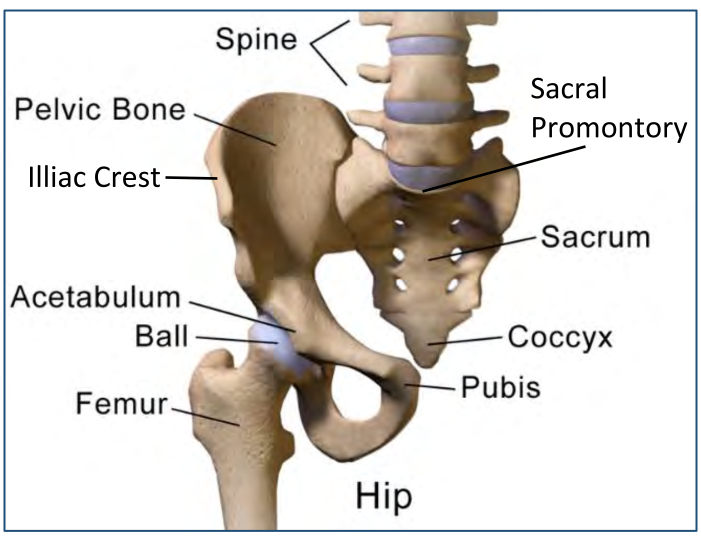

Figure 100. Illustration of the anatomy of the sacrum and coccyx.
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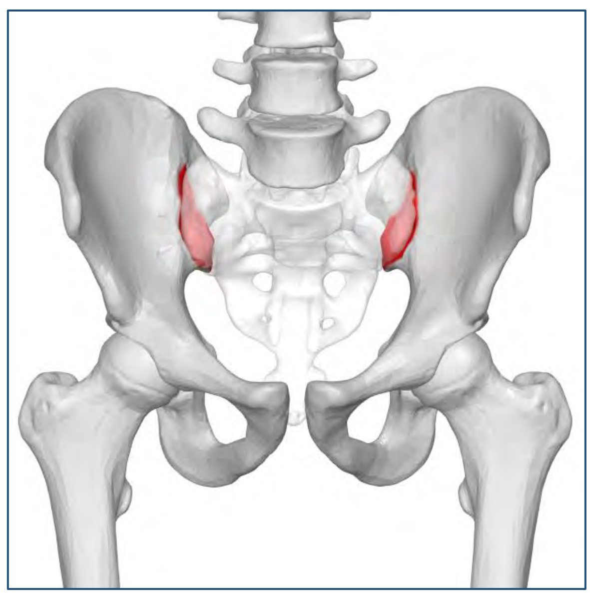

Figure 101. Illustration of the sacroiliac joints (in red). Available at commons.wikimedia.org

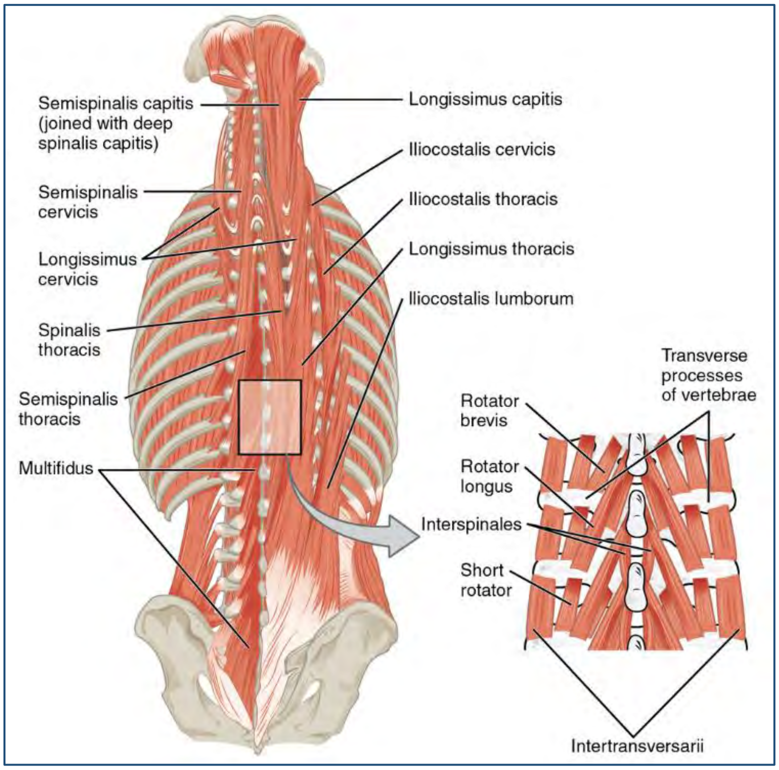

Figure 102. Illustration of the large, complex muscles of the neck and back, which move the head, shoulders, and vertebral column. Available at commons.wikimedia.org

Ligaments and Muscles

Two major ligaments support the spinal column: the anterior and posterior longitudinal ligaments. The anterior longitudinal ligament extends downward from the first cervical vertebra (C1) along the anterior surface of the vertebral surface to the sacrum. It connects the anterior aspects of the vertebral bodies and discs, and maintains stability of the joints. It also helps prevent hyperextension of the vertebral column. It is thicker in the thoracic region than in the cervical or lumbar regions.

The posterior longitudinal ligament lies within the vertebral canal, extending along the posterior surface of the vertebral bodies along the length of the canal (starting at C2); it is narrower and weaker than the anterior longitudinal ligament. The posterior longitudinal ligament helps prevent hyperflexion of the vertebral column, and also prevents protrusion of the nucleus pulposus. These ligaments are not visualized on CT scans unless calcified; thus, ligaments are best seen on MRI.

There are three main muscle groups that attach to the posterior surface of the spine. The first consists of the superficial (relative to the vertebral column) muscles of the back and shoulder, including the trapezius and latissimus dorsi, and the underlying serratus posterior muscles. The second group, collectively referred to as the paraspinal muscles, consists of the erector spinae muscles (the iliocostalis, longissimus, and spinalis), which are the chief extensors of the vertebral column. The third group, the transversospinal muscles, provides movement of the spine (**Figure 102**).

The Spinal Cord and Nerve Roots

The spinal cord resides within the vertebral foramen; it extends from the foramen magnum in the skull base to approximately the T12-L1 level, ending as it tapers into the conus medullaris.

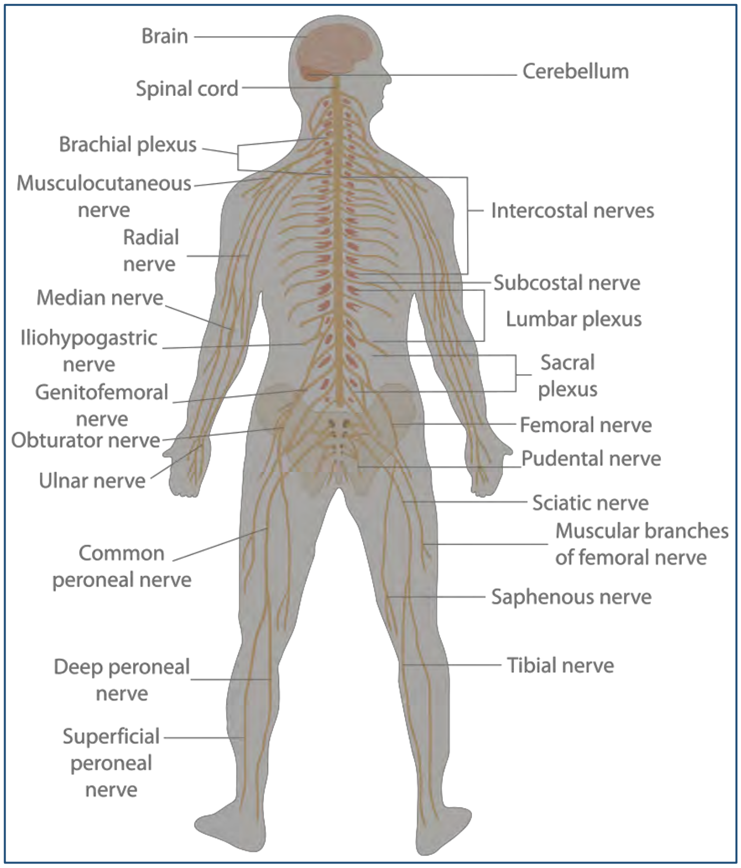

Figure 103. Illustration of the nerves and nerve plexuses of the spine. Available at commons.wikimedia.org

The spinal cord, brain, and brainstem comprise the central nervous system (CNS). Below the conus, large nerve roots travel within the vertebral foramen, exiting at specific levels at each interspace. The appearance of these large roots within the vertebral foramen is referred to as the cauda equina (horse's tail). The nerve roots exit laterally between the two adjacent pedicles. As each pair of nerve roots exit the vertebral foramina, the cauda equina becomes smaller and smaller, terminating in the sacral roots as the filum terminale. The nerve roots travel in close proximity to the posterior aspect of the intervertebral disc. Considering this anatomic arrangement, it is easy to understand how traumatic injuries in the cervical or thoracic vertebral bodies can result in varying degrees of paralysis (because the entire spinal cord may be affected), whereas injury to the lumbar vertebral bodies will produce more focal deficits.

There are four major nerve plexuses (networks of intersecting nerves) that serve the motor and sensory needs of the muscles and skin of the extremities: the cervical plexus, the brachial nerve plexus, the lumbar plexus, and the sacral nerve plexus (**Figure 103**).

Blood Vessels

Blood is supplied to the spinal cord by the spinal arteries. The major source of arterial blood is from the aorta at approximately the T11-12 level through the artery of Adamkiewicz. From this central location blood is delivered to the cord through branches that run up and down. A complex arrangement of paravertebral veins line each vertebral body (**Figure 104, Figure 105**). These veins, while rarely visualized, are a common means of transport for cancer cells, resulting in destructive metastatic lesions in the vertebral column.

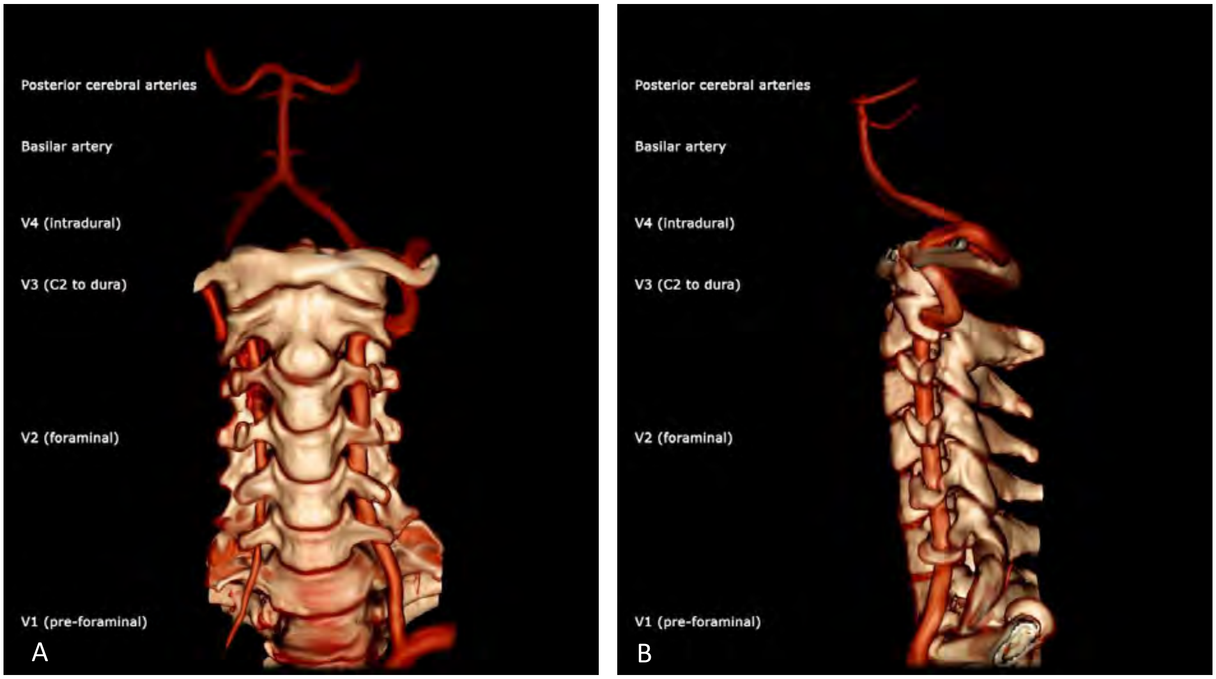

Figure 104. 3D surface-rendered CT angiogram. (A) Vertebral arteries, anterior view. Available at commons.wikimedia.org (B) Vertebral artery, lateral view. Available at https://commons.wikimedia.org

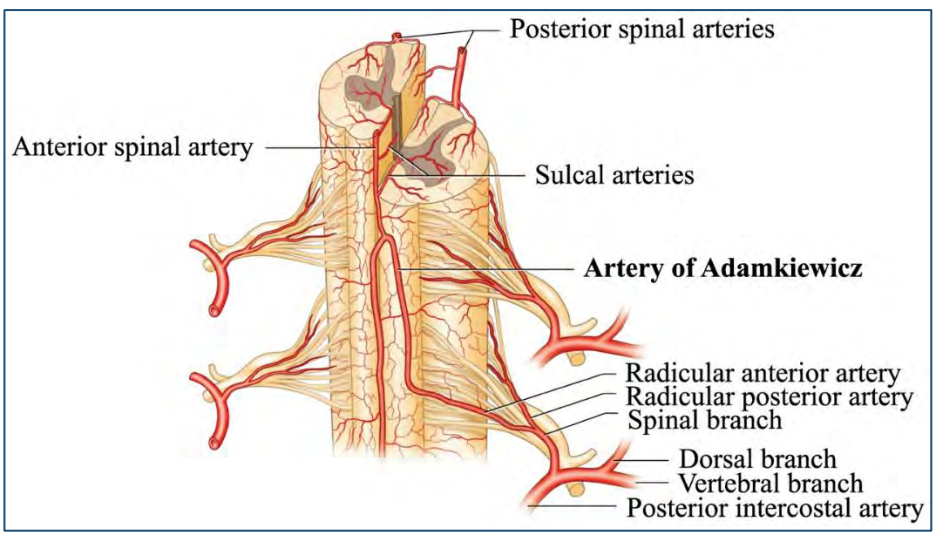

Figure 105. Illustration of vertebral blood supply. Note the artery of Adamkiewicz, which receives arterial blood from the aorta at approximately T-11 through T12. Available at anatomyclass01.us/

SPINE CT PROTOCOL DEVELOPMENT

Like CT MSK exams, it is important that the technologist and radiologist work together closely to develop CT spine protocols. Like all CT exams, spine protocols should adhere to the ALARA principle.

Most modern scanners utilize auto-mA technology that adjusts the milliamperage by patient size. When using auto-mA technology, smaller patients will receive a smaller radiation dose than will larger patients. This is accomplished by a pre-set noise factor that is the same for every patient scanned under a particular protocol. It requires less mA to reach the noise factor on a small patient than for a larger patient. Therefore, the radiation dose will be lower for a smaller patient, while the image quality will be similar to that of a larger patient. Determining the appropriate noise factor requires the assistance of the radiologist. Noise factors set too low will result in excellent quality images but at a higher than necessary radiation dose. Noise factors set too high will result in grainy images. The key is to find a balance, resulting in good quality images at a lower radiation dose.

As previously discussed, many newer scanners also utilize iterative reconstruction, which can lower radiation dose by 50% or more. Using IR also requires a balanced approach and the advice of the radiologist. Applying too much IR decreases image noise, allowing imaging at very low mA, resulting in a lower radiation dose. However, too much IR will create an overly smooth image that may not be of diagnostic quality. Not applying enough IR results in noisy images, requiring an increase in IR or mA and therefore increased radiation dose to the patient. Again, finding a balance between image quality and the lowest possible radiation dose is key.

Spine exams are imaged in helical—also called spiral—mode, resulting in a fast scan acquisition and better quality multiplanar reconstructions. Thin axial images of ≤1.25mm should be acquired or reconstructed for fine bony detail and to use for good quality sagittal and coronal reformats. Soft issue and bone algorithms should be reconstructed.

CT SCANNING OF THE CERVICAL SPINE

There are a number of clinical indications for CT scanning of the cervical spine, including trauma, neck pain, evaluation of radiculopathy, abnormalities of alignment, stenosis, fracture, and degenerative disc disease. Contrast-enhanced scans are used to diagnose or rule out infection, primary tumors, or metastatic disease.

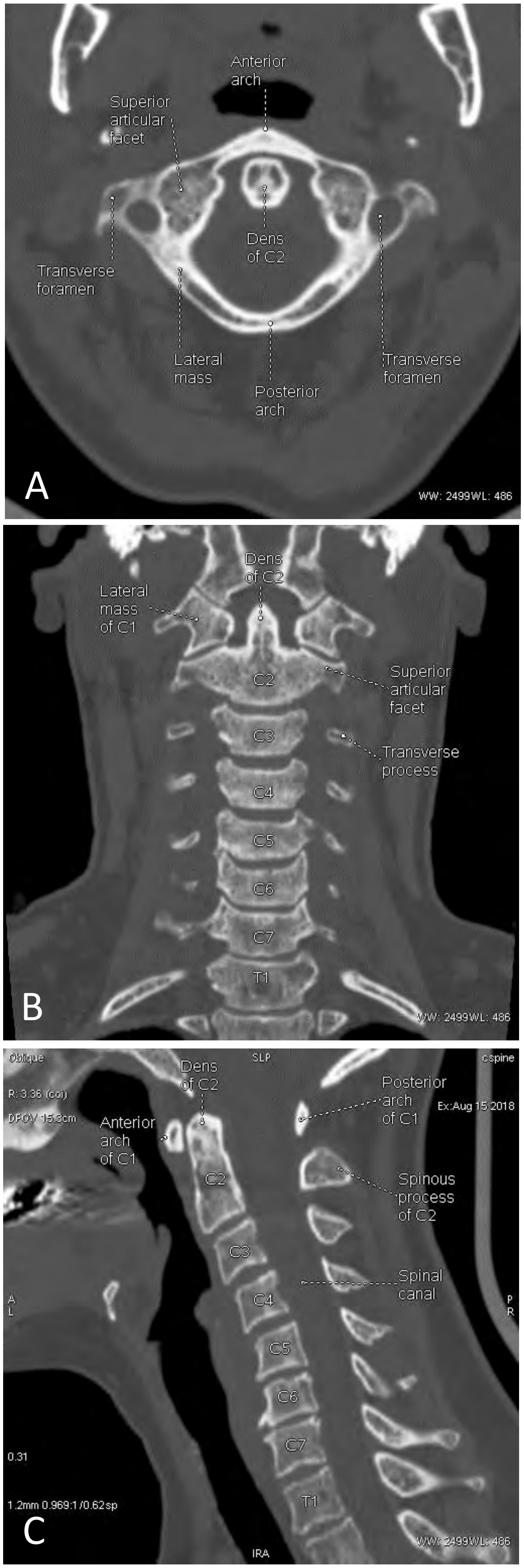

Figure 106. Cervical spine. (A) Axial CT of C1; (B) coronal and (C) sagittal MPRs.

In addition to the conditions outlined above, cervical CT scans are used to diagnose and rule out vacuum phenomenon, a disorder in which gas accumulates between the vertebral discs. This phenomenon—more common in the lumbar vertebrae—is a reliable sign of degenerative disc disease and is rare in cases of infection or tumor.

When imaging the cervical spine, the patient is placed on the table in the supine position, with the head entering the gantry first. The patient's head may be stabilized using a normal head holder, with a round sponge placed under the neck both for support and to maintain the normal curvature of the neck. Velcro®, Coban™, or tape may be used to immobilize the head. Long straps are wrapped around the patient's feet, and the patient is instructed to hold the ends in each hand and pull the shoulders downward; this technique reduces shoulder artifact. The patient should remove any dentures or metal objects in the area of the neck, chest, and head. If IV contrast is to be given, the technologist and patient should follow the procedures outlined in Chapter 1.

Anteroposterior and lateral localizer scans are taken from above the base of the skull to the sternal notch; both of these areas serve as landmarks for orienting the boundaries of the scan. Localizer scans are used to determine the level of scanning, proper image centering, and a gantry angle when necessary. The scan should extend from the craniocervical junction to C7 or T1 (**Figure 106**). Intravenous nonionic iodinated contrast is used to highlight the vasculature.

To assist the radiologist with interpretation, axial images should be annotated to identify the specific spine levels.

Multiplanar Reconstructions of the Cervical Spine

- Sagittal: on a coronal reference image, obtain images perpendicular to the cervical spine (**Figure 107**).
- Coronal: on a sagittal reference image, obtain images parallel to the cervical spine (**Figure 108**).

Figure 107. To create sagittal MPRs of the cervical spine, use a coronal reference image and obtain images perpendicular to the cervical spine.

Figure 108. To create coronal MPRs of the cervical spine, use a sagittal reference image and obtain images parallel to the cervical spine.

CT SCANNING OF THE THORACIC SPINE

Unenhanced scans of the thoracic spine are indicated when ruling out traumatic or compression fractures, and to diagnose disc herniation, degenerative disc disease, and spinal stenosis. Intravenous contrast is used to evaluate patients for tumors, metastatic disease, infection, or the presence of postoperative fibrotic scar tissue.

Patient preparation is the same as that described for the cervical spine, with removal of metallic objects from the thorax and neck. The patient should be instructed to maintain a breath-hold during the scan, or to perform shallow breathing if unable to maintain breath-hold, to decrease the risk of motion artifact. Patients should be positioned feet first and supine.

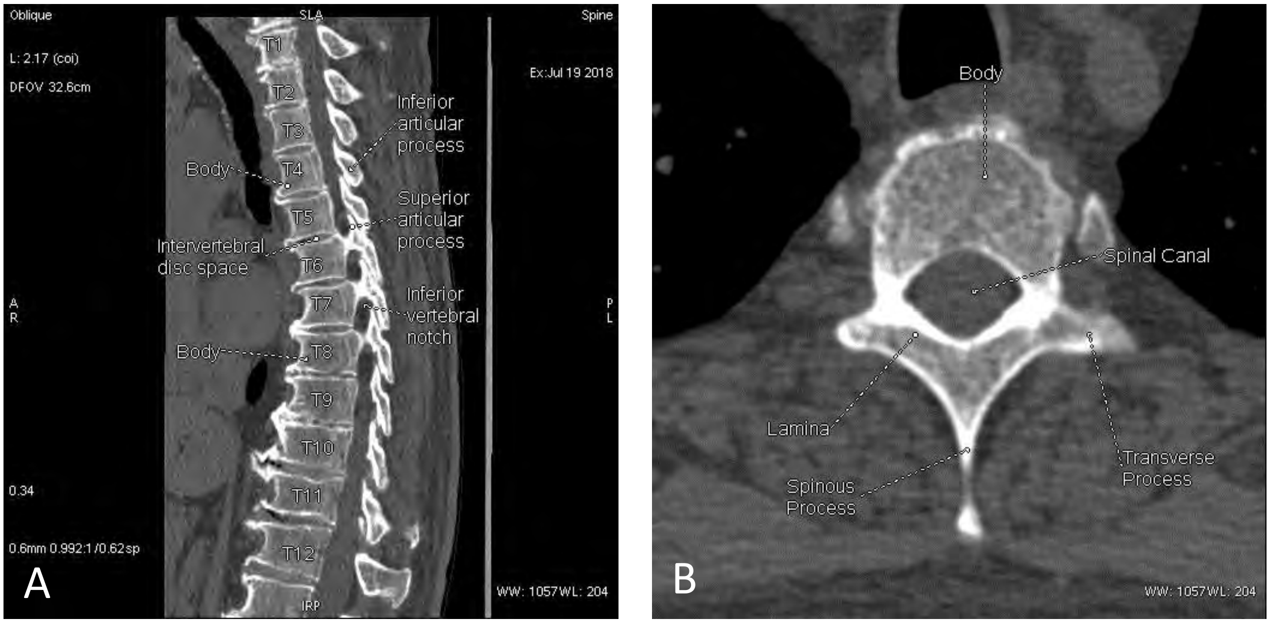

Figure 109. Thoracic spine. (A) Sagittal MPR (B) Axial CT.

The scan length should extend through the entire thoracic portion of the spine from T1 to T12 (**Figure 109**). If IV contrast is indicated, a nonionic iodinated contrast agent should be given at a minimum volume of 100mL or according to body weight, using the same methods discussed in Chapter 1. Contrast is used to highlight the vasculature and nerve plexuses.

The thoracic spine is quite long and therefore specific levels may be targeted for scanning; these levels should be determined by the referring physician from the patient's medical history. This specific information enables the radiologist to create the best protocol for the study, while minimizing radiation dose to the patient. The technologist should label the views of the MPR or 3D images. Annotating the axial images to identify the specific spine levels is particularly important, as a diagnosis will be made using both the axial and the postprocessing images. Postprocessing images are acquired using bone and standard (soft tissue) algorithms.

Figure 110. Sagittal MPR of the thoracic spine. On a reference coronal image, obtain images perpendicular to the spine.

Multiplanar Reconstructions of the Thoracic Spine

- Sagittal: On a reference coronal image, obtain images perpendicular to the spine (**Figure 110**).

- Coronals: Anterior curvature (kyphosis) of the thoracic spine is a very common condition which can make obtaining orthogonal coronal MPRs of the spine more complicated. There are two techniques for obtaining coronals of the thoracic spine.
  - Technique 1: On a reference sagittal image, obtain images parallel to the upper thoracic spine. On the same reference sagittal image, obtain images parallel to the lower thoracic spine (**Figure 111**).
  - Technique 2: Obtain a curved MPR on a sagittal reference image by maintaining a plane parallel to the entire thoracic spine. Resulting curved coronal reformat (**Figure 112**).

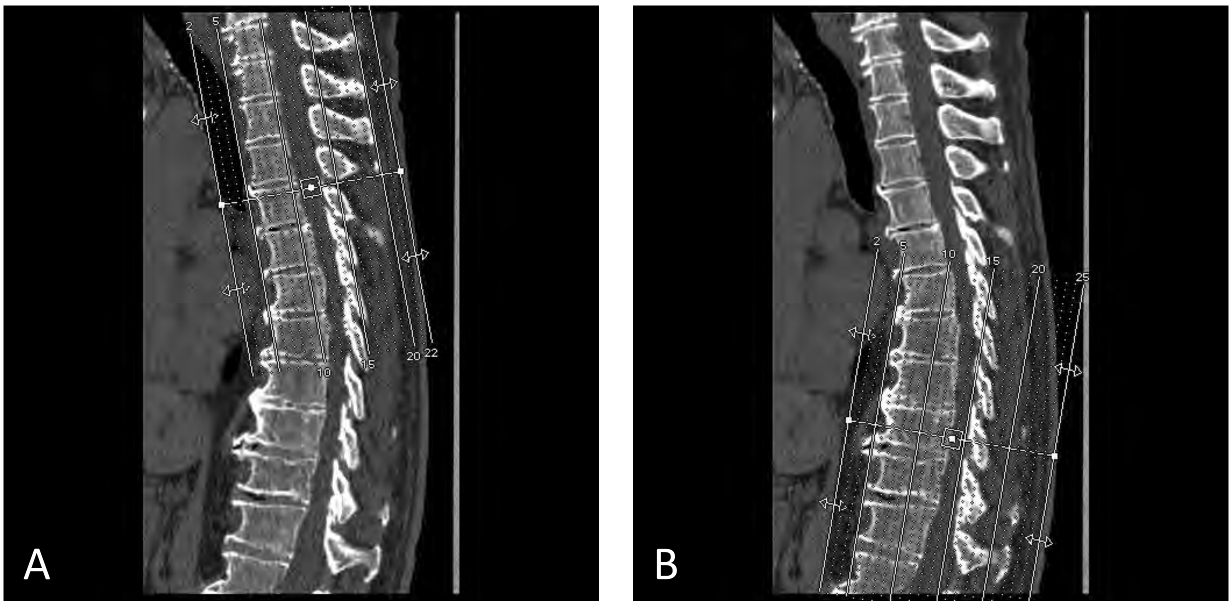

Figure 111. Coronal MPRs of the thoracic spine, Technique 1. (A) On a reference sagittal image, obtain images parallel to the upper thoracic spine. (B) On the same reference sagittal image, obtain images parallel to the lower thoracic spine.

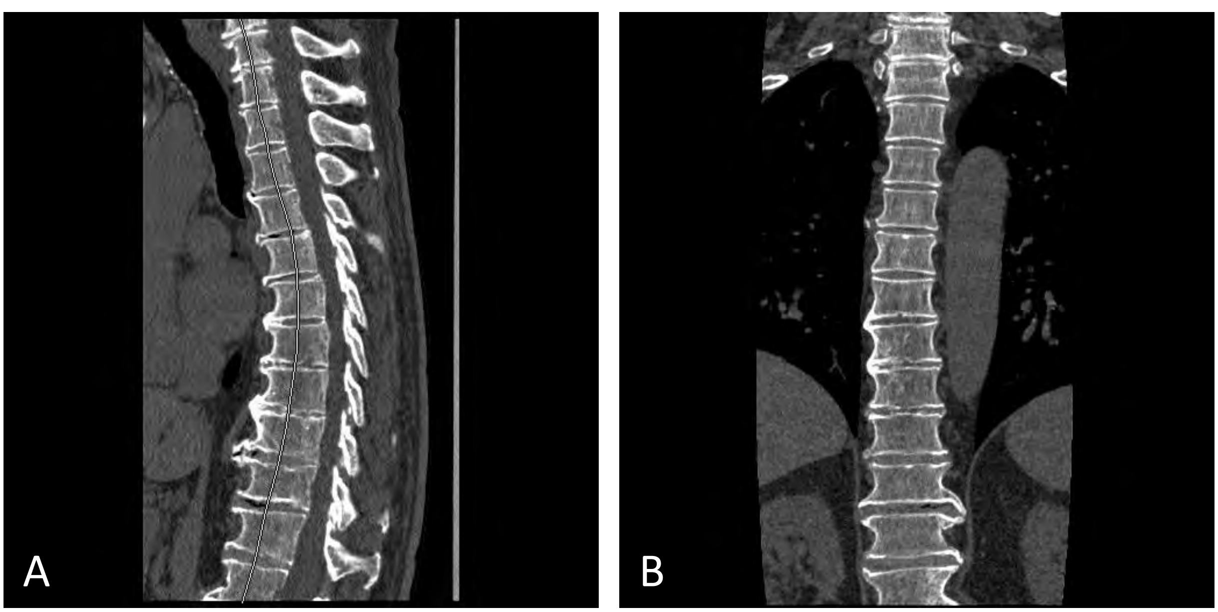

Figure 112. Coronal MPRs of the thoracic spine, Technique 2. (A) Obtain a curved MPR on a sagittal reference image by maintaining a plane parallel to the entire thoracic spine. (B) Resulting curved coronal reformat.

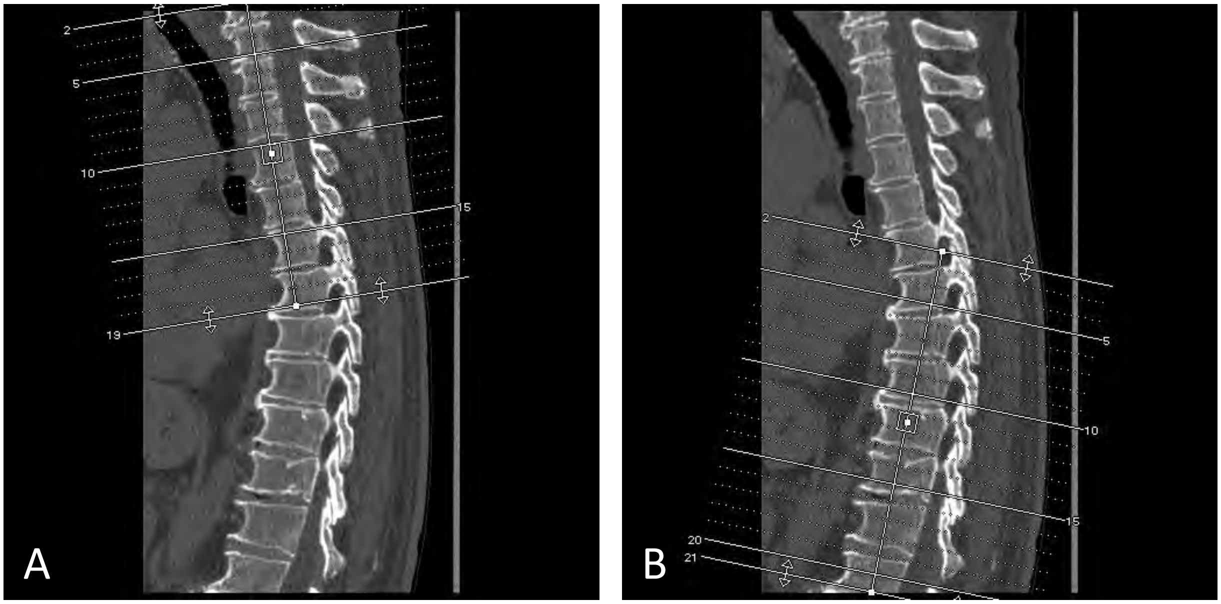

Figure 113. True axial images on a kyphotic patient. (A) On a reference sagittal image, obtain images perpendicular to the upper thoracic spine. (B) On the same reference sagittal image, obtain images perpendicular to the lower thoracic spine.

True axial images on a kyphotic patient:

- On a reference sagittal image, obtain images perpendicular to the upper thoracic spine (**Figure 113A**).
- On the same reference sagittal image, obtain images perpendicular to the lower thoracic spine (**Figure 113B**).

CT SCANNING OF THE LUMBAR SPINE

There are a number of indications for CT scanning of the lumbar spine, as shown in **Table 3**.

The single most common indication for CT imaging of the lumbar spine is for the evaluation of a herniated disc. A disc herniation means that the gelatinous nucleus pulposus protrudes through the weakened annulus fibrosis and pushes into the vertebral foramen. While this condition is most common in the lumbar spine, a disc can herniate at any level along the vertebral column. In the lumbar spine the extrusion affects nerve roots at the level of the herniation. In the cervical and thoracic spines, the spinal cord itself can be affected. The nerve tissue is affected by the physical presence of the disc itself and/or the intense inflammation caused by the presence of the abnormal tissue into the vertebral foramen pressing against the spinal cord or nerves. Disc abnormalities, such as herniated disc or degenerative changes in the spine (lumbar radiculopathy), are extremely common and are a significant cause of pain and disability. Although MRI is an excellent modality for imaging disc disease, CT is superior for displaying the bony abnormalities related to chronic disc disease.

Table 3. Indications for CT scanning of the lumbar spine.

UNENHANCED (NONCONTRAST) SCANS	CONTRAST-ENHANCED SCANS
Lumbar radiculopathy (disc disease)	Tumors
Spondylolisthesis	Metastatic disease
Osteoporosis	Infection
Spinal stenosis	Postoperative fibrotic scar tissue
Back pain	Vasculature
Vacuum phenomenon	

Figure 114. Lumbar spine. (A) Axial CT. (B) Coronal MPR showing lumbar bodies. (C) Axial CT of the soft tissue. (D) Sagittal MPR.

Patient preparation is the same as has been described for the other areas of the spine, with the addition of removal of metallic objects from the lumbar area. A pillow can be placed under the legs to maintain the natural curvature of the lumbar spine.

Anteroposterior and lateral scout scans should be used for lumbar CT scanning (**Figure 114**), with the xiphoid process used as a landmark. The scan length should cover the entire lumbar portion. If a single-slice scanner is used the gantry should be angled to the disc spaces for best visualization. IV contrast is used to highlight the vasculature and nerve plexuses. When needed, it should be given at a minimum volume of 100mL, or according to body weight, by the same methods outlined in Chapter 1.

As with other spine exams, helical scan mode should be used. Thin section images of ≤1.25mm should be acquired or reconstructed for fine bony detail and to use for sagittal and coronal MPRs. Soft tissue and bone algorithm in axial, coronal, and sagittal planes should be provided.

Multiplanar Reconstructions of the Lumbar Spine

- Sagittal: on a coronal reference image, obtain images perpendicular to the spine (**Figure 115**).
- Coronal: on a sagittal reference image, obtain images parallel to the spine (**Figure 116**).
- Axial of L5-S1 disc space: on a reference sagittal image, obtain images perpendicular to the L5-S1 disc space (**Figure 117**).

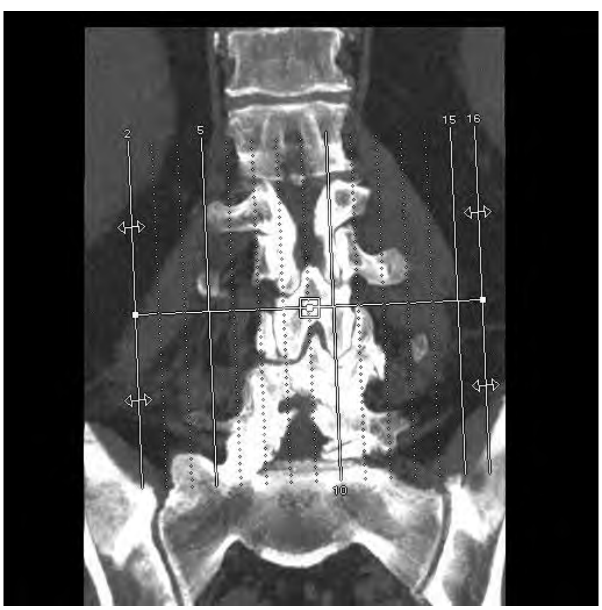

Figure 115. MPR of the lumbar spine. Sagittal: on a coronal reference image, obtain images perpendicular to the spine.

Figure 116. MPR of the lumbar spine. Coronal: on a sagittal reference image, obtain images parallel to the spine.

Figure 117. Axial image of L5-S1 disc space. On a reference sagittal image, obtain images perpendicular to the L5-S1 disc space.

CT SCANNING OF THE SACRUM AND COCCYX

CT scanning is used to assess changes in the structure and function of the sacrum and coccyx due to fracture, pyogenic sacroiliitis (an infectious process in the sacroiliac joint associated with trauma to the pelvis, intravenous drug abuse, and gynecological infections), or sacral meningocele (herniation of the meninges through a sacral bone defect).

The sacrum consists of five fused vertebrae, whose transverse processes form a large, flat lateral mass (**Figure 118**). Sacral foramina in the transverse processes allow the passage of nerves. The sacrum articulates with the pelvic bones at the sacroiliac joint through large articular surfaces on either side. On the anterior surface of the first sacral segment is the sacral promontory, a prominent ridge that is used as a landmark to separate the abdominal and pelvic cavities.

The coccyx forms the lowermost portion of the spinal column. The coccyx also consists of five fused bony segments and is located inferior to S5. Computed tomography scanning of the coccyx may be indicated in case of sciatic nerve compression or suspected fracture.

Scanning landmarks for this area are the iliac crest and the symphysis pubis, which are at the level of the greater trochanter of the femur. Scan coverage is from L1 through the entire coccyx.

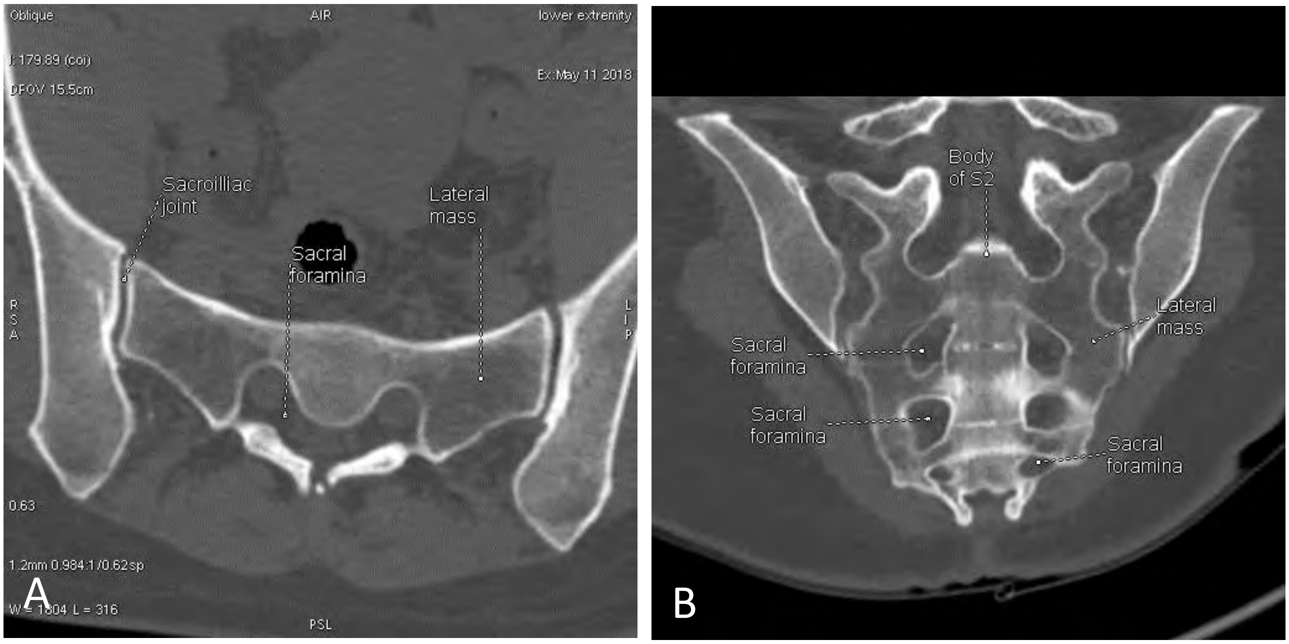

Figure 118. Sacrum. (A) Axial image. (B) Coronal MPR. (C) Sagittal MPR of the sacrum and coccyx.

Multiplanar Reconstructions of the Sacrum and Coccyx

- Sagittal: On a reference coronal image, obtain images perpendicular to the body of the sacrum (**Figure 119**).
- Coronal: On a reference sagittal image, obtain images parallel to the sacrum (**Figure 120**).
- Curved Coronal: The sacrum and coccyx have a natural curvature. To obtain true coronal MPRs, curved reformats must be reconstructed. On a sagittal reference image, create a plane that is parallel to the entire sacrum and coccyx (**Figure 121**).

Figure 119. MPR of the sacrum and coccyx. Sagittal: On reference coronal image, obtain images perpendicular to the body of the sacrum.

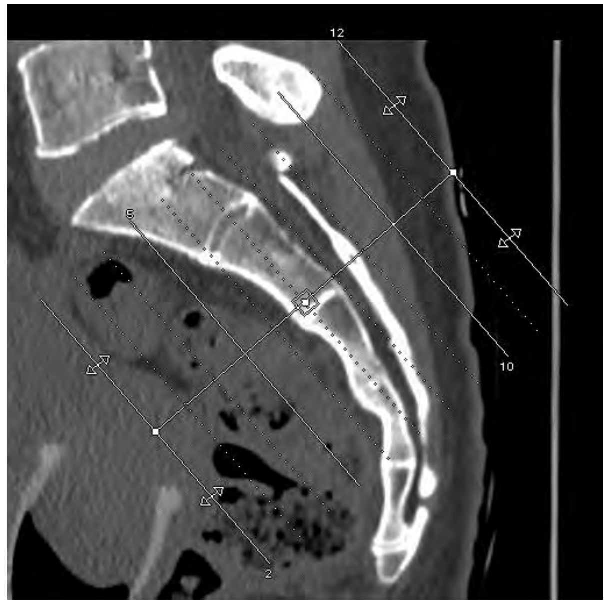

Figure 120. Coronal: On a reference sagittal image, obtain images parallel to the sacrum.

Figure 121. Curved coronal: The sacrum and coccyx have a natural curvature. To obtain true coronal MPRs, curved reformats must be constructed. (A) On a sagittal reference image, create a plane that is parallel to the entire sacrum and coccyx. (B) Resulting curved coronal image.

SUMMARY

CT scanning is a commonly requested examination for diseases of the cervical, thoracic, lumbar, and sacral spine. Different indications require significant modifications in protocols, such as single level scanning for disc disease vs. multilevel scanning for trauma or metastatic disease. Implementation of CT protocols of the spine requires teamwork between the radiologist and the technologist. With technological advances like iterative reconstruction, high-quality images of the spine can be obtained at a much lower radiation dose. The technologist must have a thorough understanding of optimal acquisition parameters in order to effectively utilize 3D and multiplanar analysis, including utilization of curved multiplanar reconstructions.

ABBREVIATION GLOSSARY

ACR	American College of Radiology
AKI	acute kidney injury
ALARA	as low as reasonably achievable
AP	anteroposterior
AVN	avascular necrosis
cm	centimeter
CNS	central nervous system
CT	computed tomography
DFOV	display field of view
DSI	dual-source imaging
eGFR	estimated glomerular filtration rate
FDA	U.S. Food & Drug Administration
FOV	field of view
HOCM	high-osmolar contrast material
IM	intramuscular
IR	iterative reconstruction
IV	intravenous
keV	kiloelectron volt
kVp	kilovoltage peak
LOCM	low-osmolar contrast material
mA	milliampere
MAR	metal artifact reduction
mAs	milliampere-seconds
MDCT	multidetector-row CT
mL	milliliter (or ‘ml’)
mm	millimeter
MPR	multiplanar reconstruction / reformatting
MRI	magnetic resonance imaging
MSK	musculoskeletal
VR	volume rendering

ILLUSTRATION ATTRIBUTIONS

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Figure 21.
LEFT: Courtesy of Blausen.com staff (2014).Available at:
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RIGHT: Courtesy of Blausen.com staff (2014). Available at:
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Figure 25. Courtesy of OpenStax. Available at:
https://cnx.org/resources/747c45c7283beabbdf2f8e385a60cbb7e3a49ac5/1124_Intrinsic_Muscles_of_the_Foot.jpg

Figure 91. Courtesy of CNX OpenStax. Available at:
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Figure 92.
LEFT: Courtesy of Blausen.com staff (2014). Available at:
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Figure 93. Courtesy of Jmarchn. Available at:
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Figure 95. Courtesy of Debivort. Available at:
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Figure 96.
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BOTTOM: Courtesy of Anatomography. Available at:
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Figure 97. Courtesy of Blausen.com staff (2014). Available at:
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Figure 103.. Courtesy of The Emirr. Available at: https://commons.wikimedia.org/wiki/File:TE-Nervous_system_diagram.svg

Figure 104. (A) Vertebral arteries based on 3D surface-rendered CT angiogram. Courtesy of Frank Gaillard. Available at https://commons.wikimedia.org/wiki/File:Vertebral_artery_3D_AP.jpg
(B).Vertebral artery, lateral view. Courtesy of Frank Gaillard. Available at
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Figure 105. Illustration of vertebral blood supply. Note the artery of Adamkiewicz, which receives arterial blood from the aorta at approximately T-11 through T12. Courtesy of anatomyclass01.us Available at
https://anatomyclass01.us/anatomy-of-vertebral-artery/anatomy-of-vertebral-artery-anatomy-of-spinal-blood-supply-2/

