Densitometry is primarily a quantitative measurement technique rather than a skeletal imaging technique. Nevertheless, there are unique aspects of skeletal anatomy in densitometry that must be appreciated to properly utilize the technology and interpret the quantitative results as well as the skeletal images.

CHARACTERIZING THE SKELETON IN DENSITOMETRY

The bones of the skeleton can be described by four characteristics, one of which is unique to densitometry. The characterizations are important, as this often determines which skeletal site is the most desirable to measure in a given clinical situation. A skeletal site may be described as axial or appendicular, weight bearing or non-weight bearing, central or peripheral, and predominantly cortical or trabecular.

The Axial and Appendicular Skeleton

The axial skeleton includes the skull, ribs, sternum, and spine (l) as shown in Fig. 2-1. In densitometry, the phrase “axial skeleton” or “axial bone density study” has traditionally referred to the lumbar spine and PA lumbar spine bone density studies. This limited use is no longer appropriate since the lumbar spine can also be studied in the lateral projection and the thoracic spine can be measured as well. The skull and the ribs are quantified only as part of a total body bone density study and as a consequence, the phrase “axial bone density study” has never implied a study of those bones although they are part of the axial skeleton. The appendicular skeleton includes the extremities and the limb girdles as shown in Fig. 2-1. The scapulae and the pelvis are therefore
The axial and appendicular skeleton. The darker-shaded bones comprise the axial skeleton. The lighter-shaded bones comprise the appendicular skeleton. Image adapted from EclectiCollections™.

part of the appendicular skeleton. The proximal femur is also obviously part of the appendicular skeleton, although it is often mistakenly described as being part of the axial skeleton. Contributing to this confusion is the current practice of including dual-energy X-ray bone density studies of the proximal femur and pelvis under the same Current Procedural Technology (CPT) code of 77080 used for DXA spine bone density studies in which the studies are described as studies of the axial skeleton (2).

**The Weight-Bearing and Non-weight-Bearing Skeleton**

Regions of the skeleton are also characterized as weight bearing or non-weight bearing. This division is obvious but not without clinical significance. The cervical, thoracic, and lumbar spine and lower extremities are weight-bearing regions of the skeleton. Portions of the pelvis are weight-bearing. The small calcaneus is also part of the weight-bearing skeleton and is perhaps the most sensitive of all the bones to the effects of weight-bearing forces. The remainder of the skeleton is non-weight-bearing.

¹ See Appendix VIII for a list of CPT codes used in bone densitometry.
The Central and Peripheral Skeleton

Skeletal sites may also be characterized as central or peripheral. This classification is unique to densitometry. The spine, in either the PA or lateral projection, is considered a central site. The proximal femur is also a central site even though it is not part of the axial skeleton like the spine. The calcaneus and the various forearm sites are all peripheral sites although the calcaneus is a weight-bearing site while the forearm sites are not. As an extension of this terminology, bone densitometers that are used to measure bone density in the spine, hip, or both are called “central” machines even though the machines may also have software that allows them to be used to measure a peripheral site like the forearm. The description of a bone densitometer as a central machine is generally reserved for dual-energy X-ray and older dual-photon absorptiometry devices. Although quantitative computed tomography (QCT) is used clinically to measure bone density in the spine, as a matter of convention QCT is rarely described as a central technique, although it would be appropriate to do so. Densitometers that can only be used to measure the distal appendicular skeleton like the forearm or calcaneus are called “peripheral” machines. Because there is no current application of quantitative ultrasound (QUS) for the central skeleton, it is understood that QUS devices are peripheral devices. As a consequence, it is not necessary to distinguish between central and peripheral QUS devices, so the term peripheral is not used in conjunction with QUS devices. Figure 2-2 illustrates the central and peripheral skeleton.

The Trabecular/Cortical Composition of the Skeleton

The skeleton is composed of two types of bone: cortical bone and trabecular bone. Cortical bone is also called compact bone or haversian bone. It is typically found in the shafts of long bones and the vertebral endplates. Trabecular bone is also called cancellous bone and is primarily found in the vertebral bodies, pelvis, and distal ends of long bones. Trabecular bone contains hematopoietic or fatty marrow. Eighty percent of the skeleton is cortical bone. The remaining 20% is trabecular bone. Trabecular bone consists of plates, arches, and struts with marrow occupying the spaces between these structures. Cortical bone is a more solid structure forming the outer casing of the bones.

Skeletal metabolism as a whole is roughly equally distributed between the two types of bones even though the skeleton is 80% cortical bone. This is because trabecular bone has a higher metabolic rate per unit of volume than cortical bone. In any one bone, however, rates of change in bone density may be greater at sites that are predominantly trabecular in composition compared to sites that are predominantly cortical. Rates of change are also greater in axial trabecular bone than in appendicular trabecular bone. If a patient is being followed over time to look for changes in the bone mineral density from a disease process or therapeutic intervention, the greatest magnitude of change will generally be seen at a site that is predominantly trabecular bone. There are certain disease processes, however, which seem to have a predilection for sites that are predominantly cortical in composition. Hyperparathyroidism, for example, may cause demineralization at predominantly cortical sites, like the femoral neck or 33% radial site. Conversely, Cushing’s disease may preferentially destroy the trabecular bone of the axial skeleton. In a disease like acromegaly, hypogonadism may cause a profound decrease in the trabecular bone of the spine while excessive growth hormone causes an increase in the density of the cortical bone of the appendicular skeleton.
Fig. 2-2. (A) and (B). The central and peripheral skeleton. The darker-shaded bones in (A) comprise the central skeleton. The darker-shaded bones in (B) comprise the peripheral skeleton. Images adapted from EclectiCollections™.

**FOREARM COMPOSITION**

The exact percentage of trabecular and cortical bone of many of the sites used in densitometry remains controversial. In a classic study, Schlenker and VonSeggen (4) quantified the average percentage of cortical and trabecular bone along the length of the radius and ulna in four cadaveric female forearms. The forearms were taken from women aged 21, 43, 63, and 85 years. The distribution and percentage of trabecular bone in the radius and ulna were similar. The maximum percentage of trabecular bone was seen in the first two centimeters proximal to the radial and ulnar styloids. The percentage of trabecular bone then dropped precipitously in both bones in a transitional region which lay between 2- and 3 cm proximal to either styloid and remained very small throughout the remainder of the proximal radius and ulna. The percentage of trabecular bone in the four subjects in the most distal 10% of the radius ranged from 50 to 67% while in the region that represented 30 to 40% of the total length measured from the styloid tip, the percentage of trabecular bone ranged from only 0.6 to 6.8%.
VERTEBRAL COMPOSITION

The composition of whole vertebra or the isolated vertebral body remains in dispute. The traditional view is that 55–75% of the calcium content of the whole vertebra is in trabecular bone. These figures are largely derived from early anatomic studies in which the methods used to arrive at such conclusions were poorly described (5, 6). The traditional view was challenged in 1987 by Nottestad et al. (7) who performed anatomic dissections of 24 vertebrae taken from 14 normal individuals, 10 of whom were women with an average age of 72 years and 4 of whom were men with an average age of 63. The vertebrae were ashed and the calcium content was assayed using atomic absorption spectrophotometry. Nottestad et al., found that trabecular bone accounted for only 24.4% of the calcium content of whole female vertebrae. Trabecular calcium accounted for 41.8% of the calcium content in the vertebral body. The percentages were less in men, averaging 18.8 and 33.5%, respectively. Eastell et al. (8) refuted this finding based on anatomic dissections of L2 from 13 individuals, 6 men whose average age was 38.5 years and 7 women whose average age was 40.9. In this study, cortical and trabecular contributions to calcium content were determined by microdensitometry and by dissection and ashing. They reported that the whole vertebra was 72% trabecular bone in women and 80% trabecular bone in men. Adjusting these figures to compensate for the expected difference between the two-dimensional measurements that were actually performed and the three-dimensional structure of whole vertebrae, the percentages of trabecular bone in whole vertebrae dropped slightly to 69% in women and 77% in men.

FEMORAL COMPOSITION

The composition of the commonly measured sites in the proximal femur was briefly studied by Baumel (Heaney RP. Personal communication, November 23, 1994) using anatomic dissection of the upper end of the femur in six cadavers (age at death 49–79 years). In this small study the percentage of trabecular bone in the femoral neck was 36.45% (± .85%) and in the trochanter 39.06% (± 3.79%). Using QCT, Kuiper et al. (9) studied the amount and distribution of cortical and trabecular bone in the femoral neck of 20 cadaveric specimens. The average age of the individuals from whom the specimens were taken was 83.2 years. In this study, trabecular bone mass accounted for 33% of the total bone mass at the mid-neck. In an earlier study from Werner et al. (10) trabecular bone mineral content at the mid-femoral neck was reported as 23.5% from 20 cadaveric specimens taken from individuals with an average age of 75 years. In the study from Kuiper et al. (9) the authors noted that trabecular bone mass appeared to decrease at a rate of 2.5% for every 1 mm increment from the femoral head to the trochanter. This raises the possibility that markedly different locations for the femoral neck region of interest among DXA manufacturers may result in the measurement of differing amounts of trabecular and cortical bone.

ALL SITES

In spite of these controversies, clinically useful characterizations of the composition of densitometry sites can be made. Table 2-1 lists the most commonly assessed skeletal sites and their relative proportions of trabecular and cortical bone (11). Note that the spine, when measured with QCT, is described as 100% trabecular bone. This is because the three-dimensional volumetric measure that is obtained with QCT allows the center of the vertebral body to be isolated from its cortical shell and the highly cortical
posterior elements. The two-dimensional areal measurement employed in DPA and DXA measurements of the spine cannot do this. Although the posterior elements are eliminated from the scan path on a lateral spine study performed with DXA, elements of the cortical shell remain. Therefore, although the measurement of the spine in the lateral projection with DXA is a highly trabecular measurement of bone density, the measurement is not a measure of 100% trabecular bone.

THE SPINE IN DENSITOMETRY

Studies of the lumbar spine performed with DPA or DXA are generally acquired by the passage of photon-energy from the posterior to anterior direction. They are properly characterized as PA spine studies. Nevertheless, these studies are often called AP spine studies, probably because plain films of the lumbar spine are acquired in the AP projection. The Lunar Expert, a fan-array scanner, actually does acquire lumbar spine bone density images in the AP direction. Compared to plain radiography, however, the beam direction in a DXA study of the spine has less influence on the appearance of the image and little if any influence on the measured BMC or BMD. Studies of the lumbar spine may also be acquired in the lateral projection using DXA. Such studies may be performed with the patient in the supine or left lateral decubitus position, depending upon the type of DXA unit employed.

Vertebral Anatomy

The whole vertebra can be divided into two major components: the body and the posterior elements. The posterior elements consist of the pedicles, the lamina, the spinous
process, the transverse processes, and the inferior and superior articulating surfaces. The appearance of the image of the spine on an AP or PA spine study is predominantly determined by the relative density of the various elements that make up the entire vertebra. Figure 2-3A is a photograph of a posterior view of the lumbar spine with the intervertebral discs removed. Figures 2-3B and 2-3C demonstrate the appearance of the spine as first the transverse processes and then the vertebral bodies are removed from the photograph. What remains in Fig. 2-3C is characteristic of the appearance of the lumbar spine on a PA DXA lumbar spine study and consists largely of the posterior elements. The posterior elements form the basis of the DXA lumbar spine image seen in Fig. 2-4. The transverse processes are eliminated from the scan field and the vertebral bodies are not well seen because they are both behind and equally or less dense than the posterior elements. In a study of 34 lumbar vertebrae taken from 10 individuals, age 61–88, the
average mineral content of the posterior elements was 47% of the mineral content of the entire vertebra (12).

The unique shapes of the posterior elements of the various lumbar vertebrae can be used as an aid in identifying the lumbar vertebrae. The posterior elements of L1, L2, and L3 have a U- or Y-shaped appearance. L4 can be described as looking like a block H or X. L5 has the appearance of a block I on its side. Figure 2-5 is a graphic illustration of these shapes. Compare these shapes to the actual posterior elements seen in Fig. 2-3C and the DXA lumbar spine study shown in Fig. 2-4. Although the transverse processes are generally not seen on a spine bone density study, the processes at L3 will sometimes be partially visible, since this vertebra tends to have the largest transverse processes. This fact can also be helpful in lumbar vertebral identification, Figures 2-6A and 2-6B.
Fig. 2-6. (A) A DXA PA spine image acquired on the Lunar DPX. This is the spine image from the study shown in Fig. 2-4, with the intervertebral disk markers and bone-edge markers removed for clarity. (B) The shapes have been outlined for emphasis.

Table 2-2
Incremental Change in BMC and BMD Between Adjacent Vertebrae in 148 Normal Women Aged 50–60, as Measured by DXA

<table>
<thead>
<tr>
<th>Vertebrae</th>
<th>Increase in BMC (g)</th>
<th>% Increase in BMC</th>
<th>Increase in BMD (g/cm²)</th>
<th>% Increase in BMD</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1–L2</td>
<td>2.07</td>
<td>13.7</td>
<td>0.090</td>
<td>7.9</td>
</tr>
<tr>
<td>L2–L3</td>
<td>2.43</td>
<td>14.8</td>
<td>0.050</td>
<td>4.3</td>
</tr>
<tr>
<td>L3–L4</td>
<td>1.13</td>
<td>5.0</td>
<td>0.004²</td>
<td>−0.8²</td>
</tr>
</tbody>
</table>

²Not statistically significant
Adapted from ref. (13) with permission of the American Society for Bone and Mineral Research.

are the spine image only from the study shown in Fig. 2-4. In Fig. 2-6B, the shapes of the posterior elements have been outlined for emphasis.

On PA or AP DXA lumbar spine studies, L1 through L4 are quantified. Although L5 can be seen, it is not usually quantified because of potential interference from the pelvis. In fact, even if labeled on the scan, some software programs will not analyze L5 unless it is deliberately mislabeled L4. L1 frequently has the lowest BMC and BMD of the first four lumbar vertebrae. In a study of 148 normal women ages 50–60, Peel et al. (13) found that the BMC increased between L1–L2, L2–L3, and L3–L4 although the increase between L3 and L4 was roughly half that seen at the other levels as shown in Table 2-2. BMD increased between L1–L2 and L2–L3 but showed no significant change between L3 and L4. The average change between L3 and L4 was actually a decline of 0.004 g/cm². The largest increase in BMD occurred between L1 and L2. The apparent
discrepancies in the magnitude of the change in BMC and BMD between the vertebrae are the result of the progressive increase in area of the vertebrae from L1 to L4. The DXA PA lumbar spine study shown in Fig. 2-4 illustrates the progressive increase in BMC and area from L1 to L4 and the expected pattern of change in BMD between the vertebral levels.

Studies from Peel et al. (13) and Bornstein and Peterson (14) suggest that the majority of individuals have five lumbar vertebrae with the lowest set of ribs on T12. Bornstein and Peterson (14) found that only 17% of 1239 skeletons demonstrated a pattern of vertebral segmentation and rib placement other than five lumbar vertebrae with the lowest ribs on T12. Similarly, Peel et al. (13) found something other than the expected pattern of five lumbar vertebrae with the lowest ribs on T12 in only 16.5% of 375 women. An additional 7.2% had five lumbar vertebrae but had the lowest level of ribs on T11. Therefore, 90.7% of the women in this study had five lumbar vertebrae. Only 1.9% or seven women out of 375 had six lumbar vertebrae. In three of these women ribs were seen on L1. This was the only circumstance in which ribs were seen on L1, and 7.5% of the entire group had only four lumbar vertebrae. In the majority of cases here, the lowest ribs were seen on T11. Table 2-3 summarizes these findings.

Knowledge of the frequency of anomalous vertebral segmentation, the characteristic shapes created by the posterior lumbar elements on a PA lumbar spine study, and the expected incremental change in BMC and BMD can be used to label the vertebrae correctly. If the vertebrae are mislabeled, comparisons to the normative databases will be misleading. The expected effect of mislabeling T12 as L1 is a lowering of the BMC or BMD at L1, which would then compare less favorably to the reference values for L1. The BMC and BMD averages for L1–L4 or L2–L4 would also be lowered. The degree to which BMC is lowered by mislabeling is substantially greater than BMD as shown in Table 2-4 (13). The assumption that the lowest set of ribs is found at the level of T12 is often used as the basis for labeling the lumbar vertebrae. As can be seen from Table 2-3, this assumption would result in the vertebrae being labeled incorrectly in 13.3% of the population. As a consequence, all of the criteria noted above should be employed in determining the correct labeling of the lumbar vertebrae. This should obviate the need for plain films for the sole purpose of labeling the vertebrae in the vast majority of instances. Figure 2-7 is a PA spine study in which the labeling of the lumbar vertebra was not straightforward. The characteristic shapes of the vertebrae are easily

<table>
<thead>
<tr>
<th>No. of Lumbar Vertebrae</th>
<th>Position of Lowest Ribs</th>
<th>% of Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>T12</td>
<td>83.5</td>
</tr>
<tr>
<td>5</td>
<td>T11</td>
<td>7.2</td>
</tr>
<tr>
<td>4</td>
<td>T12</td>
<td>2.1</td>
</tr>
<tr>
<td>4</td>
<td>T11</td>
<td>5.3</td>
</tr>
<tr>
<td>6</td>
<td>T12</td>
<td>1.1</td>
</tr>
<tr>
<td>6</td>
<td>L1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Adapted from ref. (13) with permission of the American Society for Bone and Mineral Research.
Table 2-4
The Effect of Mislabeling T12 as L1 on BMC and BMD in AP-DXA Spine Measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Difference</th>
<th>Mean %</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>1.61 g</td>
<td>11.5</td>
</tr>
<tr>
<td>L2–L4</td>
<td>3.47 g</td>
<td>8.4</td>
</tr>
<tr>
<td>L1–L4</td>
<td>4.8 g</td>
<td>8.4</td>
</tr>
<tr>
<td>BMD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2–L4</td>
<td>0.035 g/cm²</td>
<td>3.6</td>
</tr>
<tr>
<td>L1–L4</td>
<td>0.039 g/cm²</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Adapted from ref. (13) with permission of the American Society for Bone and Mineral Research.

Fig. 2-7. A DXA PA spine study acquired on the Lunar DPX. The vertebra labeled L4 has a classic block H or X shape. No ribs are seen, however, protruding from the vertebra that should be T12. It is far more likely that this represents five lumbar vertebrae with the lowest ribs on T11 than six lumbar vertebrae with the lowest ribs on T12. Also note that the BMD at L1 is higher than at L2, which is unusual. A lateral lumbar spine X-ray of this patient, shown in Fig. 2-9, confirmed a fracture at L1.

seen, but no ribs appear to be projecting from what should be T12. Note the block H shape of the vertebra labeled L4 and the visible transverse processes on the vertebra labeled L3. Statistically, it is likely that there are five lumbar vertebrae here with the lowest set of ribs on T11. The appearance of L3 and L4 would also support this labeling. Plains films acquired for the purpose of diagnosing spine fracture confirmed that the labeling shown in Fig. 2-7 is correct.

Artifacts in PA or AP Spine Densitometry

The PA lumbar spine has been, and continues to be, used extensively in densitometry for diagnosis, fracture prediction, and monitoring. Unfortunately, it is also the skeletal site most often affected by structural changes and artifacts that may limit its utility.
Vertebral Fractures

The BMD of a fractured vertebra will be increased because of the fracture itself. This increase in density could erroneously lead the physician to conclude that the bone strength is better and the risk for fracture lower than is the case. Vertebral fractures in osteoporosis frequently occur in the T7–T9 region and in the T12–L2 region (15, 16). Because DXA measurements of the lumbar spine are often employed in patients with osteoporosis, osteoporotic fractures in the lumbar spine, particularly at L1 and L2, are a common problem, rendering the measurement of BMD inaccurate if the fractured vertebrae are included. An increased precision error would also be expected if the fractured vertebrae were included in BMD measurements performed as part of a serial evaluation of BMD. Although a fractured lumbar vertebra can be excluded from consideration in the analysis of the data, this reduces the maximum number of contiguous vertebrae in the lumbar spine available for analysis. For reasons of statistical accuracy and precision, the BMD for three or four contiguous vertebrae is preferred over two vertebrae averages or the BMD of a single vertebra. Figure 2-8 illustrates a PA lumbar spine study in which a fracture was apparent at L3. Although the BMD at L3 is expected to be higher than either L2 or L4, it is disproportionately higher. The L2–L4 BMD will be increased because of the effect of the fracture on the BMD at L3. In the DXA PA lumbar spine study shown in Fig. 2-7, the image does not as readily suggest a fracture. The BMD at L1, however, is higher than the BMD at L2, which is unusual. A plain lateral film of the lumbar spine of this patient, shown in Fig. 2-9, confirmed a fracture at L1.

Fig. 2-8. A DXA PA spine study acquired on the Norland XR-36. The image suggests a loss of vertebral height and increased sclerosis at L3. Although the BMD at L3 is expected to be higher than at L2, the BMD at L3 here is markedly higher. These findings suggest a fracture at this level but this must be confirmed. In any case, the L2–L4 BMD will be increased by this structural change. Case courtesy of Norland, a CooperSurgical Company, Ft. Atkinson, WI.
Fig. 2-9. The lateral lumbar spine X-ray of the patient whose DXA study is shown in Fig. 2-7. A fracture at L1 is indicated by the arrow.

DEGENERATIVE CHANGES AND DYSTROPHIC CALCIFICATION

Other structural changes within the spine can affect BMD measurements. Osteophytes and facet sclerosis can increase the BMD when measured in the AP or PA projection. Aortic calcification will also potentially affect the BMD when measured in the AP or PA spine because the X-ray beam will detect the calcium in the aorta as it passes through the body on an anterior to posterior or posterior to anterior path. It is therefore useful to note how often these types of changes are expected in the general population and the potential magnitude of the effect these changes may have on the measured BMD in the lumbar spine.

The Effect of Osteophytes on BMD. In 1982, Krolner et al. (17) observed that osteophytes caused a statistically significant increase in the BMD in the AP spine when compared to controls without osteophytes. More recently, Rand et al. (18) evaluated a population of 144 postmenopausal women aged 40–84 years, with an average age of 63.3 years, for the presence of osteophytes, scoliosis, and aortic calcification. These women were generally healthy women referred for the evaluation of BMD because of suspected postmenopausal osteoporosis. Table 2-5 lists the percentages of these women found to have these types of degenerative changes. Based on these findings, Rand et al. estimated the likelihood of degenerative changes in the spine as being less than 10% in women under the age of 50. In 55-year-old women, however, the likelihood jumped to 40% and in 70-year-old women to 85%. Of these types of degenerative changes, however, only the presence of osteophytes significantly increased the BMD. The magnitude of the increase caused by the osteophytes ranged from 9.5% at L4 to 13.9% at L1. Cann et al. (19) also estimated the increase in BMD from osteophytes in the spine at 11%.
Table 2-5  
Frequency of Specific Types of Degenerative Changes  
in the Spines of 144 Women Aged 40–84

<table>
<thead>
<tr>
<th>Type of Degenerative Change</th>
<th>% with Change (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osteophytes</td>
<td>45.8 (66)</td>
</tr>
<tr>
<td>Osteochondrosis</td>
<td>21.5 (31)</td>
</tr>
<tr>
<td>Vascular calcification</td>
<td>24.3 (35)</td>
</tr>
<tr>
<td>Scoliosis</td>
<td>22.2 (32)</td>
</tr>
<tr>
<td>Any type</td>
<td>59.0 (72)</td>
</tr>
</tbody>
</table>

Adapted with kind permission of Springer Science and Business Media from ref. (18).

Fig. 2-10. A lateral lumbar spine X-ray of the patient whose DXA study is shown in Fig. 2-11. The arrow indicates a region of endplate sclerosis and osteophyte formation.

In 1997, Liu et al. (20) studied 120 men and 314 women, aged 60–99 years. Lumbar spine osteophytes were found in 75% of the men and 61.1% of the women. The effect of osteophytes on the BMD was sufficiently great to cause 50% of the men and 25% of the women with osteopenia to be misdiagnosed. About 20% of the men and 10% of the women with osteoporosis were misdiagnosed because of the effect of osteophytes on the BMD. In Fig. 2-10 osteophytes are clearly visible at L2 on the lateral lumbar radiograph. The appearance of this region on the DXA PA lumbar spine study in Fig. 2-11 suggests a sclerotic process at this level. Osteophytes and end-plate sclerosis are also seen on the plain film in Fig. 2-12. The effect on the DXA image of the lumbar spine, shown in Fig. 2-13 is dramatic. There is also a disproportionate increase in the BMD at L2 and L3 compared to L1 and L4.
Fig. 2-11. A DXA PA spine study acquired on the Lunar DPX. A sclerotic process is suggested at L2 by the image. The BMD is also increased more than expected in comparison to L1 and is higher than L3, which is unusual. These findings are compatible with the endplate sclerosis and osteophytes seen in Fig. 2-10.

Fig. 2-12. A lateral lumbar spine X-ray of the patient whose DXA study is shown in Fig. 2-13. The arrow indicates a region of marked endplate sclerosis.
Fig. 2-13. A DXA PA spine study acquired on the Lunar DPX. The image dramatically suggests the sclerotic process seen on the X-ray in Fig. 2-12. There is a marked increase in the BMD at L2 and L3 compared to L1 and L4.

The Effect of Aortic Calcification on BMD. Although it did not significantly increase BMD, vascular calcification was seen in 24.3% of the 144 postmenopausal women studied by Rand et al. (18). In a study of aortic calcification in 200 women aged 50 or older by Frye et al. (21) the percentage of women with aortic calcification and the effect on BMD measured in the PA lumbar spine was noted. A grading system2 for both linear calcifications and calcified plaques in the aorta was applied to lateral spine films with a grade of zero indicating neither type of calcification and a grade of two indicating the most severe degree. The percentage of women with any degree of aortic calcification and severe calcification is shown in Fig. 2-14. The percentage with any degree of aortic calcification was extremely low under age 60 but increased dramatically in women age 60 and older. The percentage of women with severe aortic calcification, however, remained low throughout the fifties, sixties, and seventies. Even in women aged 80 and older, the percentage did not exceed 30%. Table 2-6 summarizes the effect on BMD in women of any degree of aortic calcification and severe aortic calcification. Neither effect was statistically significant. These findings are similar to those of Frohn et al. (22), Orwoll et al. (23), Reid et al. (24), Banks et al. (25), and Drinka et al. (26) in which no significant effect of aortic calcification was seen on the BMD measured in the PA spine. The studies from Orwoll et al. (23) and Drinka et al. (26) were performed in men. A recent ex vivo study from Cherney et al. (27) quantified the effect of removal of the aorta on PA lumbar spine bone density. After choosing eight cadavers at random, PA lumbar spine DXA bone density studies were performed before and after the removal of the aorta. The age at death ranged from 67 to 87 years, with an average age of 79 years. Removal of the aorta resulted in an average decrease in PA lumbar spine

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2 This is not the same grading system as now used to quantify aortic calcification on plain films or lateral DXA images of the spine. See Chapter 13 for a discussion of the 24-point and 8-point grading systems in use today.
Fig. 2-14. The prevalence of aortic calcification in women aged 50 and over. From Frye MA et al. (21), with permission of Elsevier Science & Technology Journals.

Table 2-6

<table>
<thead>
<tr>
<th>Site</th>
<th>BMD</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Expected</td>
<td>Difference</td>
<td>% of Expected</td>
</tr>
<tr>
<td>BMD spine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any grade 1 or 2</td>
<td>0.93</td>
<td>0.92</td>
<td>0.01</td>
<td>101.4</td>
</tr>
<tr>
<td>Any grade 2</td>
<td>0.94</td>
<td>0.89</td>
<td>0.05</td>
<td>106.7</td>
</tr>
</tbody>
</table>

Adapted from Frye MA et al. (21) with permission of Elsevier Science & Technology Journals.

BMD of 4.64%. The authors do not describe the severity of any observed aortic calcification. Nevertheless, their results are in keeping with those from Frye et al. (21) in which a small effect on lumbar spine bone density was observed with severe aortic calcification.

Aortic calcification is not easily seen on most DXA PA lumbar spine studies. In Fig. 2-15A, however, the faint outline of the calcified aorta is visible. The aorta is easily seen on the lateral DXA image in Fig. 2-15B. Figure 2-16 shows both studies. In this case, the effects of the calcified aorta on the BMD measurement can be eliminated on the DXA lateral spine bone density study. The ability to see aortic calcification when DXA images are acquired in the lateral projection has also led to a new application for DXA: quantifying aortic calcification. This is discussed in Chapter 13.

The Effect of Facet Sclerosis on BMD. Unlike aortic calcification, facet sclerosis can have a profound effect on the measured BMD in the AP or PA projection. In the study by Drinka et al. (26) noted earlier, 113 elderly men were evaluated with standard AP and lateral lumbar spine films and dual-photon absorptiometry of the lumbar spine. A grading system for facet sclerosis was developed with a grade of 0 indicating no sclerosis and a grade of 3 indicating marked sclerosis. As shown in Table 2-7, grade 1 sclerosis had no significant effect on the BMD. Grades 2 and 3, however, markedly increased the BMD at the vertebral levels at which the facet sclerosis
Fig. 2-15. PA and lateral DXA lumbar spine images acquired on the Hologic QDR-4500. The arrow seen in (A) indicates the faint outline of the calcified aorta that is easily seen on the lateral study in (B). Case courtesy of Hologic, Inc., Bedford, MA.

Fig. 2-16. A DXA PA and lateral lumbar spine study acquired on the Hologic QDR-4500. These are the analyzed studies for the images shown in Fig. 2-15. Case courtesy of Hologic, Inc., Bedford, MA.

was found. Figure 2-17 is a PA spine BMD study in which facet sclerosis is suggested at L3 by the appearance of the image. The BMD values at L3 and L4 are also markedly higher than expected, based on the values at L1 and L2. The plain film of this patient shown in Fig. 2-18 confirms facet sclerosis at the lower lumbar levels.
### Table 2-7
The Increase in BMD from Facet Sclerosis

<table>
<thead>
<tr>
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<th>Grade 3</th>
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<tr>
<td>L1</td>
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</tr>
<tr>
<td>L2</td>
<td>0.312</td>
<td>0.472</td>
</tr>
<tr>
<td>L3</td>
<td>0.184</td>
<td>0.343</td>
</tr>
<tr>
<td>L4</td>
<td>0.034</td>
<td>0.247</td>
</tr>
<tr>
<td>Average</td>
<td>0.201</td>
<td>0.382</td>
</tr>
</tbody>
</table>

Values are in g/cm².
Adapted with kind permission of Springer Science and Business Media from Drinka et al. (26).

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**Fig. 2-17.** A DXA PA lumbar spine study acquired on the GE Lunar DPX. There is a marked increase in the BMD between L2 and L3, which is maintained at L4. The image faintly suggests sclerosis in the region of the facet joints at L3 and L4. This is more dramatically seen in the plain film of this patient shown in Fig. 2-18.

### OTHER CAUSES OF ARTIFACTS IN PA AND AP LUMBAR SPINE STUDIES

Potential causes of apparent increases in the BMD in the AP or PA lumbar spine have been identified by Stutzman et al. (28). These include pancreatic calcifications, renal stones, gallstones, contrast agents, and ingested calcium tablets in addition to osteophytes, aortic calcification, and fractures. The effect on the BMD of these artifacts would appear to be greater in the patient with low bone density than in the patient with high bone density (29, 30). Using cadaveric specimens, Morgan et al. (29) placed a variety of commonly encountered artifacts, such as surgical clips, gallstones, calcium tablets, and kidney stones lateral to L1 or L3. One cadaveric specimen had a high BMD and the other had a low BMD. Surgical clips in the gallbladder region or a gallstone did not significantly affect the L1–L4 BMD in either cadaveric specimen. However, there was a significant effect on the L1–L4 BMD in the low BMD specimen from bra wires and calcium tablets lateral to L1 or L3. In a companion study, Morgan et al. (30) noted that some artifacts, because of their very high density, appear as “black hole” on a PA spine DXA study rather than white. This included tantalum surgical clips, which are often used in vascular surgery. Tantalum clips are useful for a variety of reasons, not the least of which is their lack of ferromagnetic potential, which allows for magnetic...
Fig. 2-18. A lateral lumbar spine X-ray of the patient whose bone density study is shown in Fig. 2-17. The arrows indicate sclerotic regions in the posterior elements.

resonance imaging. Tantalum pellets are also used as radiographic markers because they are radiopaque. Another artifact which produced a “black hole” was a lead bullet. In contrast, titanium or stainless steel clips appeared white. Once again, the most pronounced effects of the “black hole” artifact tantalum clips were seen in the low-BMD cadaveric specimen. When tantalum clips were placed over L3 of a cadaveric specimen with the high L1–L4 BMD, the L1–L4 BMD was largely unaffected. In the low-BMD cadaveric specimen, however, when eight tantalum clips were placed over L3 or L4 placed lateral to L3, the L1–L4 BMD was increased. A Hologic spine phantom was used to assess the effects of a 0.45-caliber lead bullet placed over L3. The bullet created a “black hole” artifact at L3. The BMC, area, and BMD were all significantly greater at L3 and at L1–L4 with the bullet compared to the phantom BMD without the bullet overlying L3. The authors noted that their findings were obtained using a Hologic Discovery W. If the DXA software automatically excludes non-physiologic densities from the analysis, very dense objects overlying the spine would not be expected to increase the measured BMD. However, the effect of this approach is a “black hole” of another type in this case, the hole is in the data. Few studies exist on the effects of ascites on bone density measured in the PA projection. In one such study, Labio et al. (31) found that ascites can falsely lower the BMD measured in the PA projection in patients with cirrhosis. In the study

3 See Chapter 4 for a discussion of spine phantoms, including the Hologic spine phantom.
Fig. 2-19. A DXA PA lumbar spine study acquired on the Lunar DPX. The image suggests increased density at L3 and L4, but there is also a linear vertical lucency over L4. The BMD values are markedly increased at L3 and L4. This patient had previously undergone an L3–L4, L4–L5 interbody fusion and laminectomy at L4. Although the laminectomy alone would decrease the BMD at L4, the fusion mass has increased the BMD at L3 and L4 dramatically.

Fig. 2-20. A DXA PA spine study acquired on the Lunar DPX. The image is unusual at L4, with what appears to be an absence of part of the posterior elements. This was confirmed with plain films. This should decrease the BMD at L4.

noted previously from Cherney et al. (27), the removal of two intervertebral discs with chondrocalcinosis resulted in a decrease in BMD of 11.93%. Figures 2-19, 2-20, and 2-21 illustrate other structural changes in the spine that will affect the BMD measured in the PA projection.
Fig. 2-21. A DXA PA spine study acquired on the Lunar DPX. The image suggests a marked sclerotic reaction at L4 and L5. There is also a marked increase in the BMD at L4 compared to L3. This sclerotic process was thought to be the result of an episode of childhood discitis. The patient was asymptomatic.

**The Effect of Vertebral Rotation on PA Lumbar Spine Bone Density**

Rotation of the vertebral bodies is often a component of idiopathic scoliosis although it is not frequently seen in adult-onset degenerative scoliosis. To study the effect of vertebral body rotation on bone density measured in the lumbar spine with DXA, Girardi and colleagues (32) utilized a cadaveric spine with intact soft tissue. The spine, which spanned the ninth thoracic vertebra to the sacrum, was mounted at both ends in the neutral midline position. Calibration markings on the mounts allowed for the spine to be rotated in 10° increments to a maximum of 60° in either direction. The bone density of L1 through L4 was measured with DXA in duplicate in the neutral position and at each 10° increment in both directions.

The vertebral segment area increased with increasing rotation up to 50° in either direction from midline and then decreased between 50° and 60°. The BMC remained relatively constant throughout rotation except at the extreme of 60° on either side of the midline at which point it decreased. Because BMD is determined by dividing the BMC by area, the increasing area with rotation resulted in BMD decreasing with rotation to either side of the midline. From neutral to 60°, the decrease in BMD was almost 20%. In clinical practice then, rotation of the spine for any reason should be expected to cause an apparent decrease in bone density when measured with DXA. This becomes relevant in the patient with roto-scoliosis, although the effect on BMD at the spine from the expected combination of rotation and facet sclerosis in such a patient is not straightforward.

**The Spine in the Lateral Projection**

The effect on BMD measured in the AP or PA projection from aortic calcification, facet sclerosis, osteophytes, and other degenerative changes in the spine can be nullified by quantifying the bone density of the spine in the lateral projection as shown in Fig. 2-15B. In addition, the highly cortical posterior elements and a portion of the
cortical shell of the vertebral body can be eliminated from the measurement, resulting in a more trabecular measure of bone density in the spine. The measurement is not a 100% trabecular measure as portions of the cortical vertebral body shell will still be included in the measurement. In addition to the elimination of artifact or confounding degenerative changes, the lateral spine BMD measurement is desirable in those circumstances in which a trabecular measure of bone density is indicated and particularly in circumstances in which changes in trabecular bone are being followed over time. The higher metabolic rate of trabecular bone compared to cortical bone should result in a much larger magnitude of change in this more trabecular measure of bone density compared to the mixed cortical-trabecular measure of bone density in the PA spine.

Vertebral identification in the lateral projection can be difficult. The lumbar vertebrae are generally identified by the relative position of the overlapping pelvis and the position of the lowest set of ribs. The position of the pelvis tends to differ, however, when the study is performed in the left lateral decubitus position compared to the supine position. Rupich et al. (33) found that the pelvis overlapped L4 in only 15% of individuals when studied in the supine position. Jergas et al. (34) reported a figure of 19.7% for L4 overlap for individuals studied in the supine position. In DXA studies performed in the left lateral decubitus position, pelvic overlap of L4 occurred in 88% of individuals in the study by Peel et al. (13). In the other 12%, the pelvis overlapped L5 in 5% and the L3–L4 disc space or L3 itself in 7%. As a consequence, while the position of the pelvis tends to identify L4 in most individuals scanned in the left lateral decubitus position, it also eliminates the ability to accurately measure the BMD at L4 in those individuals. The ribs are less useful than the pelvis in identifying the lumbar vertebrae. Rib overlap of L1 can be expected in the majority of individuals whether they are studied in the supine or left lateral decubitus position (13). This may not be seen, however, in the 12.5% of individuals whose lowest set of ribs is on T11.

While the location of the pelvis and the presence of rib overlap aid in identification of the vertebrae, they also limit the available vertebrae for analysis. When a lateral spine DXA study is performed in the left lateral decubitus position, L4 cannot be analyzed in the majority of individuals because of pelvic overlap. L1 is generally not analyzed because of rib overlap, regardless of whether the study is performed supine or in the left lateral decubitus position. Rupich et al. (33) also found that rib overlap L2 in 90% of individuals studied in the supine position. It was estimated that rib BMC added 10.4% to the L2 BMC. As a consequence, when lateral DXA studies are performed in the left lateral decubitus position, L3 may be the only vertebra that is not affected by either pelvic or rib overlap. In the supine position, L3 and L4 are generally unaffected. This means that depending upon the positioning required by the technique, the value from a single vertebra or from only a two vertebrae average may have to be used. This is undesirable, although sometimes unavoidable, from the standpoint of statistical accuracy and precision.

If the vertebrae are misidentified in the lateral projection, the effect on BMD can be significant. In the study by Peel et al. (13) misidentification of the vertebral levels would have occurred in 12% of individuals in whom the pelvis did not overlap L4 in the left lateral decubitus position. If L2 was misidentified as L3, the BMD of L3 was underestimated by an average of 5.7%. When L4 was misidentified as L3, the BMD at L3 was overestimated by an average of 3.1%. Although spine X-rays are rarely justified for the sole purpose of vertebral identification on a DXA study performed in the
PA or AP projection, this may occasionally be required for DXA lumbar spine studies performed in the lateral projection. Analysis may be restricted to only one or two vertebrae because of rib and pelvic overlap. This reduces the statistical accuracy and precision of the measurement. Because of this reduction in accuracy, consideration should be given to combining lateral DXA spine studies with bone density assessments of other sites for diagnostic purposes.

THE PROXIMAL FEMUR IN DENSITOMETRY

Proximal Femur Anatomy

The gross anatomy of the proximal femur is shown in Fig. 2-22A and B. In densitometry, the proximal femur has been divided into specific regions of interest. The proximal femur studies shown in Fig. 2-23A and B illustrate these regions, which are based upon the anatomy shown in Fig. 2-22A and B. Ward’s area is a region with which most physicians and technologists are not familiar. Ward’s triangle, as it was originally called, is an anatomic region in the neck of the femur that is formed by the intersection of three trabecular bundles as shown in Fig. 2-24. In densitometry, Ward’s triangle is a calculated region of low density in the femoral neck rather than a specific anatomic region. Because the region in densitometry is identified as a square, the region is generally now called Ward’s area instead of Ward’s triangle. The total femur region of interest encompasses all of the individual regions: the femoral neck, Ward’s area, the trochanteric region, and the shaft. Each of these regions within this one bone contains a different percentage of trabecular and cortical bone as noted in Table 2-1.

Fig. 2-22. (A) The proximal femur as viewed from the front. The lesser trochanter is behind the shaft of the femur. (B) The proximal femur as viewed from behind. The lesser trochanter is clearly seen to be a posterior structure (Adapted from McMinn RMH, Hutchings, RT, Pegington J, Abrahams PH. Colour atlas of human anatomy. Third edition, 1993: 267–268. © 1993 Mosby, with permission from Elsevier.).
Fig. 2-23. DXA proximal femur studies. Five regions of interest are defined. (A) Hologic QDR 4500 DXA study. Case courtesy of Hologic, Inc., Bedford, MA. (B) Lunar Prodigy. Four regions of interest are labeled for emphasis on this study. The total ROI, which is not outlined, includes the neck, trochanter, and shaft.

The Effect of Rotation on BMD in the Proximal Femur

The lesser trochanter is an important anatomic structure from the perspective of recognizing the degree to which the femur has been rotated during positioning for a proximal femoral bone density study. Precision in proximal femur bone density testing is highly dependent upon reproduction of the degree of rotation of the proximal femur
Fig. 2-24. Ward’s triangle, indicated by the letter W, is formed by the intersection of bundles of trabeculae in the femoral neck (Adapted from McMinn RMH, Hutchings, RT, Pegington J, Abrahams PH. Colour atlas of human anatomy. Third edition, 1993:271. © 1993 Mosby, with permission from Elsevier.).

From study to study, in positioning the patient for a proximal femur study, internally rotating the femur 15–20° will bring the femoral neck parallel to the plane of the scan table. This rotation is accomplished with the aid of positioning devices provided by the manufacturers. In this neutral position BMD values in the femoral neck are the lowest. If the femoral neck rotation is increased or decreased from this position, the femoral neck BMD value will increase. Table 2-8 illustrates the magnitude of the increase in BMD in a cadaver study from Goh et al. (35). In another cadaver study from Cheng et al. (36), the mean increase in BMD at the femoral neck was 2.8% in the anteverted position compared to the desired neutral position with the femoral neck axis parallel to the plane of the scan table. The authors also noted that the BMD increased with increasing anteversion. The trochanteric BMD was also increased with anteversion but

<table>
<thead>
<tr>
<th>Cadaver No.</th>
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<th>External Rotation from Neutral of</th>
<th>Internal Rotation from Neutral of</th>
</tr>
</thead>
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<tr>
<td></td>
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<td>15°</td>
<td>30°</td>
</tr>
<tr>
<td>1</td>
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</tr>
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</tr>
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</tr>
<tr>
<td>4</td>
<td>0.946</td>
<td>0.977</td>
<td>1.005</td>
</tr>
</tbody>
</table>

Reproduced with kind permission of Springer Science and Business Media from Goh et al. (35).
less than the femoral neck at 0.2%. The apparent length of the neck of the femur will
decrease as rotation is increased or decreased from the neutral position. In the study
from Cheng et al. (36) the femoral neck axis length decreased 2.4% with anteversion
compared to the neutral position. When the neck of the femur is parallel to the plane of
the scan table, the X-ray beam passes through the neck at a 90° angle to the neck. With
changes in rotation, the neck is no longer parallel to the scan table and the beam enters
the neck at an angle that is greater or lesser than 90°. The result is an apparent shortening
of the length of the neck and an increase in the mineral content in the path of the beam. The
combination results in an apparent increase in BMD. In one of the few in vivo studies
performed to look at the effects of rotation on proximal femur BMD, Lekamwasam
et al. (37) found that BMD at the femoral neck and trochanter increased with increasing
external rotation and decreased with internal rotation beyond the neutral position. Based
on their established precision at the femoral neck, a significant change in BMD was seen
in 12% of the subjects after internal rotation and 8% after external rotation. The only
visual clue to consistent rotation is the reproduction of the size and shape of the lesser
trochanter. Because the trochanter is a posterior structure, leg positioning in which the
femur has not been rotated sufficiently internally tends to produce a very large and
pointed lesser trochanter. Excessive internal rotation of the proximal femur will result
in a total disappearance of the lesser trochanter. The size of the lesser trochanter in the
DXA proximal femur image in Fig. 2-25A indicates correct internal rotation. This can
be compared to the size of the lesser trochanter seen in the DXA proximal femur study
in Fig. 2-25B. The lesser trochanter is very large and pointed, indicating insufficient
internal rotation. Although this would be undesirable in a baseline study of the proximal
femur, follow-up studies using the proximal femur in this patient should be done with
this same degree of rotation. Any change in rotation from the baseline study would be
expected to affect the magnitude of change in the BMD, decreasing the precision of the
study.

Fig. 2-25. Images of the proximal femur acquired during a DXA study. In (A) the lesser trochanter is clearly
seen but is small and rounded, indicating proper internal rotation of the proximal femur during positioning.
Compare this lesser trochanter to the lesser trochanter seen in (B). This is the same patient seen in (A) but
here the proximal femur was not rotated internally sufficiently causing the lesser trochanter to appear large
and pointed.
The Effect of Leg Dominance on BMD in the Proximal Femur

In general, there does not seem to be a significant difference in the bone mineral density in the regions of the proximal femur between the right and left legs of normal individuals (38, 39, 40, 41). Leg dominance, unlike arm dominance, does not appear to exert a significant effect on the bone densities in the proximal femur and is not used to determine which femur should be studied. When proximal femur bone density studies first became available, the default or automatic positioning mode for the proximal femur was the right side. This was subsequently changed to the left side. The reason for the change, however, only reflected the orientation of the machine and the technologist’s ease of access to the left leg.

The Effect of Scoliosis, Osteoarthritis, Osteophytes, Surgery, and Fracture on BMD in the Proximal Femur

Structural changes and artifacts that interfere with DXA proximal femoral BMD measurements occur less often than at the spine. Osteoarthritic change in the hip joint may cause thickening of the medial cortex and hypertrophy of the trabeculae in the femoral neck, which may increase the BMD in the femoral neck and Ward’s area (42). The trochanteric region is not apparently affected by such change and has been recommended as the preferred site to evaluate patients with osteoarthritis of the hip (43). Osteophytes in the proximal femur are apparently much less common than osteophytes in the lumbar spine (20). They also appear to have little effect on the bone densities measured in the proximal femur. In patients with scoliosis, however, lower bone densities have been reported on the side of the convexity (44). If a “worst-case” measurement is desired, the bone density in the proximal femur should be measured in the femur on the side of the convexity. Proximal femur fracture and surgically implanted prostheses will render measurements of bone density in the proximal femur inaccurate.

If osteoarthritis or some other process restricts the ability of the patient to rotate the femur properly, the study should not be done. An attempt should be made to scan the opposite proximal femur if possible. Similarly, if pain restricts the patient’s range of motion such that the femur cannot be properly positioned, the study should not be done as the results will be not be valid.

Single vs. Dual Proximal Femur Bone Density Measurements

As noted earlier, studies suggest that leg dominance does not have a clinically significant effect on the mean BMD measured in the right and left proximal femurs and is thus not used to determine which femur should be measured (38–41). Artifact, degenerative change, or positioning difficulties may cause the densitometrist to decide to measure one side as opposed to the other. With the increasing speed of scan acquisition and the development of software, which can combine the performance of right and left proximal femur DXA scans into one study, some authorities have suggested that both proximal femurs be routinely measured for reasons of precision, diagnosis, and serendipity.

Precision is unquestionably improved when the mean of the right and left region of interest (ROI) is used instead of the BMD from either single ROI. Shepherd et al. (45) using the GE Lunar Prodigy and Hologic Dephi concluded that dual femur scan modes decreased the already superb precision by approximately 25% compared to single femur results. Mazess et al. (46) concluded that precision was improved by 30% compared to
single femur results. Similarly, White et al. (47) concluded that femoral neck precision was improved with the use of the mean bilateral femoral neck BMD rather than the femoral neck BMD from a single femur. The improvement in precision creates the potential to better detect changes in bone density and therefore the utility of the proximal femur ROIs for monitoring changes in BMD.

The potential benefit of studying both proximal femurs on the diagnosis of osteoporosis is not as straightforward. The World Health Organization (WHO) criteria for the diagnosis of osteoporosis utilize specific cut points based on the number of standard deviations below the young adult mean bone density that the measured bone density lies. These criteria are now generally expressed in terms of the T-score. But because these are specific cut points, a change in the T-score of as little as 0.1 may result in a different diagnosis based on the WHO criteria. Because some treatment guidelines utilize T-score cut points as well, a change of as little as 0.1 in the T-score might result in the invocation of a different approach to clinical management based on the guideline. While the WHO diagnostic criteria and treatment guidelines from various organizations have proven to be extraordinarily useful, shifts in diagnostic categories or treatment approaches caused by potentially very small changes in the T-score are not a strong argument for the routine performance of bilateral proximal femur studies. Cole (48) has argued to the contrary. In a retrospective study of 313 postmenopausal women who underwent bilateral proximal femur studies, Cole found that the diagnosis changed from normal to osteopenia in 5.7% of the women when the lowest single T-score from either femur was used compared to the use of T-scores from only one femur, using WHO criteria and applying them to the total hip, femoral neck, or trochanter. The diagnosis changed from osteopenia to osteoporosis in 3.3%. Based on the 1998 National Osteoporosis Foundation treatment guidelines, the clinical management of the patient potentially changed in 5.4%. In a much larger study, Petley et al. (41) obtained BMD measurements of the PA lumbar spine and right and left femoral necks in 2372 women. The authors identified subjects with an osteoporotic femoral neck on one side and a normal or osteopenic femoral neck on the other. They then excluded those patients with an osteoporotic lumbar spine in order to determine the percent of patients in which knowledge of the second femoral neck might have changed the diagnosis from normal or osteopenic to osteoporotic. Importantly, they also excluded patients whose bone density differed between right and left femoral neck by less than the precision at the femoral neck. The authors found that there was diagnostic agreement between the two proximal femurs in 81.2% of the patients, leaving 18.8% in which there was not. When patients with an osteoporotic spine were then excluded, only 3.3% of the remaining patients had an osteoporotic femoral neck on one side and a normal or osteopenic femoral neck on the other. When the authors further excluded those patients whose right and left femoral neck BMD differed by less than the precision at the femoral neck, only 2.2% of the patients had an osteoporotic femoral neck on one side and a normal or osteopenic femoral neck on the other. The authors concluded that studies of both proximal femurs would have altered the categorization from normal or osteopenic to osteoporotic in 1.2% of the cases if only the right proximal femur had been studied and in 0.9% if only the left proximal femur had been studied. In this study

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4 See Chapter 9 for a discussion of the WHO criteria. They are also found in Appendix IV.
of 2372 women only three (0.1%) women had a normal femoral neck and an osteoporotic femoral neck. A higher percentage, 11.5% had a normal femoral neck and an osteopenic femoral neck. When the PA lumbar spine and proximal femur are studied, it would appear that there is little additional diagnostic yield from a bilateral femur study. However, if the PA lumbar spine is not studied or deemed not reliable, a stronger case can be made for a bilateral proximal femur study.

A final argument in favor of studying both proximal femurs is simply to ensure that a baseline study is obtained on both, in case one femur becomes unsuitable for study in the future. This is not clinically unreasonable, as the study of both proximal femurs adds little to the time of the study, radiation exposure remains very low and reimbursement is not changed from that for a single femur DXA study. There is no data at present to support this approach but that in no way diminishes the logic behind it.

THE FOREARM IN DENSITOMETRY

Nomenclature

The nomenclature used to describe the various sites in the forearm that are assessed with densitometry is confusing. Commonly measured sites are the 33% or one-third site, the 50%, and 10% sites, the 5 and 8 mm sites, and the ultradistal site. The sites designated by a percentage are named based on the location of the site in relationship to the overall length of the ulna. This is true for the site regardless of whether the site is on the ulna or the radius. In other words, the 50% site on the radius is located at a site on the radius which is directly across from the site on the ulna that marks 50% of the overall ulnar length, not 50% of the overall radial length. The 5 and 8 mm sites are located on either bone at the point where the separation distance between the radius and ulna is 5 or 8 mm respectively. In Fig. 2-26 the approximate location of these sites is

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5 Although a mathematical conversion of one-third to a percentage would result in a value of 33.3%, the site when named as a percentage is called the 33% site and is located on the radius or forearm at a location that represents 33%, not 33.3% of the length of the ulna.
indicated. The 33% and 50% sites are both characterized as mid-radial sites while the 10% site is considered a distal site. The ultradistal site is variously centered at a distance of either 4% or 5% of the ulnar length. There is nothing inherent in the definition of distal, ultradistal, and proximal, however, that specifies the exact location of sites bearing these names. In Figures 2-27, 2-28, 2-29, and 2-30 the location of variously named regions of interest from several different DXA forearm devices can be compared.

The clinically important difference between these sites is the relative percentages of cortical and trabecular bone found at the site. Table 2-1 summarizes the percentages of cortical and trabecular bone at the various sites on the radius. These values are transferable to sites at the same location on the ulna.

**The Effect of Arm Dominance on Forearm BMD**

Unlike the proximal femur, arm dominance has a pronounced effect on the bone density in the forearm. In healthy individuals the BMC at the 33% radial site differs by 6% to 9% between the dominant and non-dominant arms (49). A difference of 3% has been reported at the 8 mm site (50). If the individual is involved in any type of repetitive unilateral arm activity, the difference between the dominant and non-dominant arm densities will be magnified to an even greater extent. Two studies of tennis players, an activity in which the dominant arm is subjected to repeated loading and impact, illustrated the effect of unilateral activity. In a study by Huddleston et al. (51) the BMC in the dominant forearm at the 50% radial site measured by SPA was 13% greater than in the non-dominant arm. In a more recent study from Kannus et al. (52) using DXA, the side-to-side difference in BMD in tennis players averaged 10.8% at the distal radius and 9.9%
Fig. 2-28. A DXA study of the forearm acquired on the Osteometer Dexcel DTX-200. The region of interest is called the distal (DIS) region and begins at the 8 mm separation point. Values are given for each bone and for both bones combined. This distal region of interest is not the same as the distal region of interest shown in Fig. 2-27.

Fig. 2-29. A DXA study of the forearm acquired on the Lunar Prodigy. The two primary regions of interest are the ultradistal (UD) and 33% regions. These are similar but not identical in location to the distal and proximal regions seen in the study in Fig. 2-27.
Fig. 2-30. A DXA study of the forearm acquired on the Hologic QDR-4500. Three regions of interest are shown here. An ultradistal (UD), mid, and one-third region of interest are indicated. The one-third region of interest is located similarly to the 33% region of interest shown in Fig. 2-29. Note that the mid region here is clearly not located at a point that would correspond to 50% of ulnar length. It is between the ultradistal and one-third sites.

at the mid-radius. The corresponding values in the non-tennis playing controls were only 3.4 and 2.5%, respectively. Because of these recognized differences, the non-dominant arm has traditionally been studied when the bone content or density is quantified for the purposes of diagnosis or fracture risk assessment. Most reference databases for the machines in current use have been created using the non-dominant arm. Comparisons of the dominant arm to these reference databases would not be valid. Some manufacturers supply databases for the dominant arm that can be used for comparisons if the dominant arm is to be studied. The operator’s manual for the densitometry device should be consulted to determine which arm was used to create the database(s) provided by the manufacturer.

The Effect of Artifacts on BMD in the Forearm

The forearm sites are relatively free from the confounding effects of most of the types of artifacts that are often seen in the lumbar spine. The presence of a prior fracture in the forearm will affect the BMC or BMD measurements in the forearm close to the prior fracture site. A study from Akesson et al. (53) suggested that in women with a prior fracture of the distal radius, the BMC was increased by 20% at the distal radius of the fractured arm in comparison to the non-fractured arm, irrespective of arm dominance. It is obviously important for the technologist to ask if the patient has experienced a prior wrist or forearm fracture. Unfortunately, this same study from Akesson et al. noted that in a group of older women who were known to have previously had a distal radial fracture, many of the women did not recall the fracture or incorrectly recalled which
arm was fractured. It was noted, however, that the forearm most often fractured was the dominant forearm.

The effect of movement during a forearm scan was quantified by Berntsen et al. (54) using single-energy X-ray absorptiometry forearm studies performed as part of the Tromsø Study.6 Over 7900 forearm studies were evaluated for the presence of movement artifacts, which were graded I–III depending on the severity. Movement artifacts were found in 14.2% of the studies. Berntsen et al. found that movement was more likely in older individuals with the prevalence of movement artifact increasing to 20% of the scans in the oldest age group. Movement artifact appeared to slightly decrease the measured BMD. The effect on precision was studied in a subset of 111 patients. The authors found a doubling of precision7 when movement was present, which was independent of the severity of the movement artifact. Although this study was performed utilizing only one type of forearm densitometer, the authors noted that these results should be applicable to any forearm scan for which data acquisition requires 3–5 minutes.

THE METACARPALS, PHALANGES, AND CALCANEUS

Other skeletal sites can be studied using the techniques available today. The metacarpals, phalanges, and calcaneus were among the very first sites studied with the older techniques of radiographic photodensitometry and radiogrammetry. These sites are increasingly utilized today with the advent of computerized radiographic absorptiometry, computerized radiogrammetry, and peripheral DXA and ultrasound units. Figure 2-31 illustrates the anatomy of the hand and the location of the metacarpals and phalanges. The middle phalanges of the index, long, and ring fingers are the phalangeal regions most often quantified. Figure 2-32 illustrates the appearance of the phalanges on a computerized radiographic absorptiometry study while Fig. 2-33 illustrates the appearance of the metacarpals on a computer-assisted radiogrammetry study. The anatomy of the calcaneus8 is illustrated in Fig. 2-34. The calcaneus contains an extremely high percentage of trabecular bone and is exquisitely sensitive to weight-bearing activities. Both the phalanges and the calcaneus have been shown to be useful sites for the prediction of hip fracture risk (55, 56, 57). The relative percentages of trabecular and cortical bone for the phalanges and calcaneus are found in Table 2-1.

BONE PHYSIOLOGY

Although the relevance of bone physiology to clinical densitometry may not be immediately apparent, the density of bone as measured in clinical practice is the outcome of the physiology and pathophysiology of bone. The densitometrist is generally not concerned with the development of bone or changes in bone that occur at the microscopic level. Nevertheless, the bone density at any given time and the changes in bone density

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6 The Tromsø Study is a population-based study, conducted in Tromsø, Norway, that focuses on lifestyle-related diseases such as osteoporosis.
7 See Chapter 11 for a discussion of precision. Because precision is a measure of variability, an increase in precision is undesirable.
8 The calcaneus is also known as the os calcis or heel.
that the densitometrist observes and interprets are the direct outcomes of bone physiology and pathophysiology. A brief review of these processes is appropriate when considering skeletal anatomy in densitometry.

Bone is composed of both organic and inorganic materials. Approximately 70% of the weight of a bone is from its inorganic material (58). An additional 5–8% is from water and the rest is from its organic material. Of the inorganic material, approximately 95% is calcium phosphate crystalline hydroxyapatite and the remaining 5% are various impurities such as carbonate, chloride, or fluoride.9 The organic material found in bone is primarily type I collagen. It also contains a variety of non-collagenous proteins and cells.

As noted previously, the bones in the skeleton belong to either the axial or appendicular skeleton. The long bones in the appendicular skeleton can be divided into four

9 These impurities can replace the phosphate in the hydroxyapatite and may alter its physical properties.
**Fig. 2-32.** A radiographic absorptiometry analysis of the mid-phalanges of the index, long, and ringer fingers. Case provided courtesy of CompuMed, Inc., Los Angeles, CA.

**Fig. 2-33.** An X-ray image from computer-assisted radiogrammetry of the metacarpals of the index, long, and ring finger. Case provided courtesy of Sectra Pronosco, Denmark.
sections: the epiphysis, physis or growth cartilage, metaphysis, and diaphysis. The epiphysis is found at both ends of the long bone and develops from an ossification center that is separate from the rest of the bone. The growth cartilage separates the epiphysis from the metaphysis. After longitudinal growth has ceased in the adult, the growth cartilage disappears leaving only a remnant called the epiphyseal line to mark the boundary between the epiphysis and metaphysis. The metaphysis is a cone-shaped region that tapers to blend with the middle portion of the shaft of the long bone called the diaphysis. The cavity of a long bone is called the medullary canal and is bounded by cortex-marrow junction.

Within each bone are different surfaces such as the periosteal surface, cortical-endosteal surface, and trabecular-endosteal surface (59). These surfaces are also called envelopes because they create and bind specific spaces within the bone. The periosteum is the outermost bone surface. As an envelope, it encloses the hard and soft tissues within a bone. Both types of endosteal surfaces are the bone surfaces adjacent to marrow. The endosteal envelope encloses the majority of the soft tissues of the bone. The endosteal surfaces may thus be considered the innermost bone surfaces. Consequently, bone tissue itself is inside the periosteal envelope and outside the endosteal envelope. The response of bone cells to various stimuli can vary widely among the cells found in the periosteal and cortical-endosteal and trabecular-endosteal envelopes. The periosteal envelope increases throughout life, being predominantly a region in which net bone gain takes place. The cortical-endosteal envelope also expands throughout life, usually outpacing the increase in the periosteal envelope. As a consequence, the cortex of the bone tends to thin with advancing age. The trabecular-endosteal envelope is a bone surface with a high rate of metabolic activity in comparison to the other surfaces.

**Bone Growth, Modeling, and Remodeling**

The densitometrist works with bone at the macroscopic or gross level. From this perspective, bone appears to be a hard, inert substance. In fact, bone is extremely active at the microscopic level undergoing growth, modeling, or remodeling, depending on the stage of life. Longitudinal growth occurs in the skeleton of the child and adolescent from proliferation of cartilage at the growth plates, which subsequently undergo calcification. Modeling refers to a change in the shape or axis of a bone in response to mechanical or
physiologic stresses. Remodeling is the process in which old bone is removed and new bone is synthesized (60). This is a lifelong process by which the body renews the bone. Both modeling and remodeling are relevant to the work of a densitometrist although a densitometrist does not need to be expert in either. A basic understanding of the physiology and pathophysiology of the remodeling process, in particular, is adequate.

**BONE MODELING**

Bone modeling or the change in shape or orientation of the bone in response to physiologic or mechanical force is governed by Wolff’s Law (61), which states:

> Every change in the form and function of bones, or of their function alone, is followed by certain definite changes in their internal architecture and equally definite secondary alteration in their external conformation, in accordance with mathematical laws.

In brief, Wolff’s Law states “form follows function.” The brilliance of bone modeling is meeting the needs of mechanical usage in the most efficient manner with the smallest amount of bone tissue necessary. This prevents the skeleton from being so heavy that mobility is impossible or so fragile that mobility results in fracture.

The emphasis in modeling is the change in shape or alignment of the bone. There is also a net gain of bone tissue that occurs during this process. This results in new periosteal bone with little gain in endosteal bone. Modeling, unlike remodeling, is largely absent after age 20.

**BONE REMODELING**

Parfitt posed the question of why bone, which survives for thousands of years after death, needs to remodel itself during life (62). At the microscopic level, the answer to this question would explain the events that trigger the bone remodeling process. A potential explanation lies in the basic functions of the skeleton.

The primary function of the skeleton is mechanical. According to Parfitt (59) the skeleton maintains the shape of the body and provides protection for the internal organs. It also provides a framework for the bone marrow and for the transmission of muscular contractions that result in movement and ambulation. A second function of the skeleton is the regulation of extracellular fluid (ECF) composition, in particular calcium homeostasis, through exchanges of the bone mineral with the extracellular fluid. Remodeling is postulated to be necessary for the skeleton to sustain both of these functions.

The mechanical competence of the skeleton is maintained by stochastic\(^{10}\) and targeted remodeling. In theory, the purpose of stochastic remodeling is to prevent fatiguedamage by removing bone before it reaches some critical age. That age may be different depending on the bone. Targeted remodeling would repair bone that has already undergone fatigue damage. It appears that a bone turnover rate of 2–5% per year is sufficient to maintain the skeleton’s mechanical competence.

In the axial skeleton, adjacent to red marrow, the rate of bone turnover is 15–35% per year. This rate of bone turnover greatly exceeds the 2–5% per year needed to sustain mechanical competence. The comparatively excessive remodeling appears to sustain the ECF regulatory functions of the skeleton. This dichotomy in remodeling rates also

\(^{10}\) Stochastic is an adjective that means random or subject to probabilities.
suggests that ECF regulatory functions are primarily limited to the trabecular bone of the axial skeleton, with the primary function of the trabecular bone of the appendicular skeleton being mechanical.

**THE BASIC MULTICELLULAR UNIT IN BONE REMODELING**

Bone remodeling is accomplished by the basic multicellular unit (BMU). The BMU is a group of cells whose actions result in the resorption of bone and subsequent new bone formation to replace the resorbed bone. The end result of the activity of the bone BMU is the creation of a discrete packet of bone called the bone structural unit (BSU) (60). There can be many BSUs made at different times within any one bone. These are held together by a collagen-free connective tissue that histomorphometrists call a cement line.

Within the BMU are two major cell types: the osteoclast and the osteoblast. The BMU also contains blood vessels, nerves, and connective tissue. The osteoclast is a large, multinucleated cell of hematopoietic origin derived from macrophages (63). The osteoclast is the cell responsible for bone resorption. The lifespan of the osteoclast is not definitely known but is postulated to be only days. The cell does clearly undergo a preprogrammed death or apoptosis.

The osteoblast is the cell responsible for bone formation. It is presumed to originate from a pluripotent mesenchymal stem cell, although its origins and various stages of development are not well understood (64). It is believed to pass through an osteoprogenitor stage on its way to becoming a preosteoblast and, finally, a mature osteoblast. An osteoblast that has become encased in its own mineralized matrix further matures into an osteocyte. An osteoblast lying on a quiescent bone surface will develop into a flattened cell called a lining cell.

In cortical bone a tunnel is created by osteoclastic bone resorption. This resorption or erosion period lasts approximately 30 days (60). Preosteoblasts are drawn to the tunnel and mature into osteoblasts. Bone matrix is synthesized by the osteoblasts and after a period of time known as the mineralization lag time, it is mineralized. The formation period lasts about 90 days, during which time the erosion tunnel is refilled with new bone that has a central or Haversian canal. The new bone is laid down in layers of alternating direction called lamellar bone. The lamellar bone surrounding the Haversian canal is the newly formed BSU.

In trabecular bone, osteoclastic bone resorption occurs on the surface of the bone rather than by tunneling. Over a period of about 40 days, a resorption cavity is created. Preosteoblasts migrate into the resorption cavity and mature into osteoblasts. Matrix is synthesized and subsequently mineralized over a period of approximately 150 days. The resorption cavity is filled with this new, lamellar bone, becoming a trabecular BSU.

Under normal circumstances in the mature skeleton, bone resorption and bone formation are coupled. At any given remodeling site, bone formation predictably follows bone resorption such that resorbed bone is replaced with an equal amount of new bone. This predictable sequence of events in both cortical and trabecular bone remodeling is called

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11 The term basic multicellular unit (BMU) is considered synonymous with bone remodeling unit (BRU).
“ARF,” an acronym for activation, resorption, and formation (60). In disease states like osteoporosis, even though the ARF sequence remains, resorption and formation may be uncoupled leading to an imbalance in resorption and formation and a net bone loss. The rate at which BMUs are activated initiating bone resorption is called the activation frequency. In some disease states, the activation frequency may increase or decrease producing changes in bone mass.

Ninety to 95% of the newly secreted bone matrix is type I collagen. Before the collagen fibrils are formed, procollagen molecules undergo cleavage of their extension peptides. These amino- and carboxy terminal peptides from the procollagen molecule are quantifiable as measures of bone formation. During bone formation, osteoblasts secrete osteocalcin, which is a protein containing 49 amino acids. Bone-specific alkaline phosphatase (BAP or BSAP) is found on the surface of osteoblasts. During bone formation, BSAP is released into the circulation. Both osteocalcin and BSAP can be quantified as measures of bone formation as well.

Once the triple helix type I collagen fibrils are formed, the mechanical strength of the collagen is enhanced by cross linking the fibrils with modified forms of the amino acid lysine. These collagen crosslinks are called pyridinium crosslinks. During bone resorption, free forms of pyridinoline and deoxypyridinoline are released and can be measured in the urine as markers of bone resorption. The C-terminal and N-terminal telopeptides associated with the cross linking sites on the collagen fibrils are also cleaved from the collagen fibrils during resorption and can be measured as markers of bone resorption as well.

The markers of bone resorption and bone formation are collectively called biochemical markers of bone remodeling or bone turnover. Assays for some of these markers are available for clinical use. In disease states characterized by high rates of bone remodeling, levels of markers of both bone formation and resorption may be increased while the converse is true in states of reduced bone remodeling. In clinical practice, it is not uncommon to measure two markers at any one time to assess the status of bone remodeling. One marker will be a formation marker such as BSAP and the second will be a marker of bone resorption, such as N-telopeptide. Measurable changes in the levels of these markers occur more quickly than changes in bone density, making them attractive as a means of assessing therapeutic efficacy of bone active interventions. Many of the anti-resorptive bone-active agents used in clinical medicine cause a reduction in the levels of biochemical markers as a result of their efficacy in reducing bone turnover. An anabolic agent like 1–34 rhPTH appears to stimulate bone formation and as a consequence, the levels of markers of bone formation are increased in response to therapy. In clinical practice, however, the precision of biochemical markers is still poor compared to DXA for assessing therapeutic efficacy. Largely because of the poor precision, cost, and availability of markers, there are no general recommendations for the use of markers in clinical practice at the present time (65). However, when markers are used,

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12 The full name of these peptides is procollagen I carboxy-terminal or nitrogen-terminal extension peptide (PICP or PINP).
13 Osteocalcin is also known as bone GLA protein.
14 See Chapter 11 for a discussion of the importance of precision.
performance of markers in duplicate is generally recommended to improve the precision of the test.

High levels of bone turnover have been associated with increased risk of fracture, independent of the level of bone density \(^{(66, 67, 68)}\). Both the number and the depth of the resorption cavities in trabecular bone have been proposed as a mechanism by which vertebral fractures may occur that is partially independent of bone density \(^{(69, 70)}\). As a corollary, reductions in bone turnover that occur more quickly than changes in bone density in response to anti-resorptive therapies may be responsible for some of the initial rapid reduction in vertebral fracture risk seen with such therapies \(^{(71)}\). Markers of bone remodeling are appearing in clinical practice as part of the assessment of patients with metabolic bone disorders and often in conjunction with the assessment of bone density. Although the densitometrist may not be directly involved with the interpretation of biochemical markers, an understanding of the origin and implications of these markers should prove increasingly useful.

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