Radiology

Multidetector CT of Blunt Abdominal Trauma[1]

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The morbidity, mortality, and economic costs resulting from trauma in general, and blunt abdominal trauma in particular, are substantial. The "panscan" (computed tomographic [CT] examination of the head, neck, chest, abdomen, and pelvis) has become an essential element in the early evaluation and decision-making algorithm for hemodynamically stable patients who sustained abdominal trauma. CT has virtually replaced diagnostic peritoneal lavage for the detection of important injuries. Over the past decade, substantial hardware and software developments in CT technology, especially the introduction and refinement of multidetector scanners, have expanded the versatility of CT for examination of the polytrauma patient in multiple facets: higher spatial resolution, faster image acquisition and reconstruction, and improved patient safety (optimization of radiation delivery methods). In this article, the authors review the elements of multidetector CT technique that are currently relevant for evaluating blunt abdominal trauma and describe the most important CT signs of trauma in the various organs. Because conservative nonsurgical therapy is preferred for all but the most severe injuries affecting the solid viscera, the authors emphasize the CT findings that are indications for direct therapeutic intervention.

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Learning Objectives:

After reading the article and taking the test, the reader will be able to:

- List imaging findings of important injuries that result from blunt abdominal trauma.
- Explain current concepts of CT technique that are relevant to evaluation of patients with blunt trauma.
- Apply CT findings for adequate therapy for patients with blunt abdominal trauma.

Radiology

Trauma is the leading cause of death in the United States for men and women under the age of 45 years and the fourth overall cause of death for all ages (1). Trauma also has a substantial economic impact on the health care system, accounting for over one-third of all emergency department visits and resulting in over $80 billion per year in direct medical care costs (1). In 2007, over 180 000 people died of trauma (1), and abdominal injuries contributed to a large number of these deaths. In patients with severe polytrauma, substantial resources are used in the evaluation of the abdomen and pelvis for possible injuries. The main reason is that many injuries that affect organs and structures of the abdomen and/or pelvis are treatable, and pa-

Essentials

- Because conservative nonsurgical therapy is preferred for all but the most severe injuries affecting the solid viscera, accurate diagnosis is heavily reliant on the findings of CT examinations performed adequately and in a timely fashion and accurately interpreted CT images.

- A typical blunt abdominal CT protocol includes portal venous phase images and selective acquisition of delayed and/or arterial phase images (CT angiograms).

- When acquired, radiation dose settings for arterial and delayed phase images should be adjusted to yield a decrease in tube current and correspondingly higher image noise.

- Orthogonal plane reformations should be used routinely to improve the accuracy for diagnosing certain injuries, such as those affecting the diaphragm and spine.

- In patients with hemoperitoneum, the presence of active extravasation and the rate of bleeding have a more direct effect on patient care decisions than does the volume of free blood in the abdomen.

tients may recover without sequelae. Thus, a prompt and accurate diagnosis is critical, and the radiologist plays a pivotal role in the decision-making process.

Mechanisms of Injury and Pathophysiology of Abdominal Injuries in Blunt Trauma

The most common causes of blunt abdominal trauma are motor vehicle collisions, falls from height, assaults, and sports accidents (1). Considerable forces are usually required to injure the solid and hollow viscera in the abdomen. Three basic mechanisms explain the damage to the abdominal organs: deceleration, external compression, and crushing injuries (2). Rapid deceleration generates shear forces that create movement of adjacent structures in opposite directions, causing tears at the points of fixation, such as vascular pedicles and mesenteric attachments. In crushing injuries, massive forces crush the abdominal contents between the abdominal wall and the spine or bones of the chest wall. Finally, extreme external compression may cause a sudden increase in intraabdominal pressure, possibly resulting in rupture of hollow viscera.

In approximate order of frequency, the most commonly injured abdominal organs and structures are the spleen, liver, kidneys, small bowel and/or mesentery, bladder, colon and/or rectum, diaphragm, pancreas, and major vessels (3), and multiple organs are often affected simultaneously. Various factors determine the specific association of organs injured: the energy delivered at impact, the part of the body struck first, the body habitus, and, in the case of motor vehicle accidents, the use (and type) of a restraint device. Frontal impacts (such as those undergone by unrestrained drivers) injure structures near the midline of the body: sternum, aorta, heart, spleen, left hepatic lobe, pancreas, and small bowel. Left lateral impacts cause left-sided injuries: left rib cage, left lung, spleen, left kidney, and left lobe of the liver. Right lateral impacts cause right-sided injuries: right rib cage, right lung, right hepatic lobe, and right kidney. Knowledge of these common patterns of

injury and the associations of the organs involved are helpful when interpreting computed tomographic (CT) studies of trauma victims (4).

Initial Workup and Evaluation

Appropriate care of the trauma patient entails a multidisciplinary effort that requires speed and efficiency. Proper coordination of the initial care team (of which the radiologist is an integral member) demands the ability to make fast rational decisions with a thorough understanding of the pathophysiology of shock. In cases of multiple trauma, the primary assessment should prioritize detection of potentially lethal but treatable injuries that may require immediate intervention to maintain circulating blood volume to perfuse vital organs and allow adequate gas exchange and oxygenation of blood. These injuries include pericardial tamponade, tension pneumothorax, profuse external bleeding, and unstable pelvic fractures. For this reason, bedside radiographs of the chest and pelvis are usually included in the initial set of tests performed in polytrauma patients, shortly after arrival at the hospital. Alternatively, if the decision to perform a CT examination of the chest and abdomen has been made, these bedside radiographs can be replaced with the corresponding digital scout images.

Persistent clinical findings of occult ongoing hemorrhage indicate the chest, abdomen, and/or pelvis as the likely source(s). The evaluation should then focus on rapid detection and treatment of catastrophic bleeding. Continued intraabdominal hemorrhage in the setting of a compromised hemodynamic status, despite aggressive resuscitation efforts, is usually an indication for emergent surgery. A FAST (focused assessment

with sonography for trauma) study that shows abundant free fluid (blood) in the abdomen often precedes the decision to perform emergency laparotomy. In FAST, the following spaces are evaluated with ultrasonography for the sole purpose of detecting hemorrhage: pericardium, hepatorenal fossa, left subphrenic space, right and left paracolic gutters, and pouch of Douglas (5,6). However, not all clinically important abdominal injuries have associated hemoperitoneum (7).

Patients who do not require immediate laparotomy or intervention then undergo further diagnostic testing. Clinical examination is notoriously unreliable. In fact, missed abdominal injuries (especially of the bowel and pancreas) are a well-known cause of increased morbidity and mortality in patients who survive the initial phases of multiple trauma (8–10). This occurs because patients commonly have concomitant injuries (thereby diverting the responding physicians' attention) or an altered mental state from drug and/or alcohol intoxication.

With the marked decrease in the use of diagnostic peritoneal lavage (11,12), diagnosis of abdominal injuries now relies almost exclusively on the accurate interpretation of findings from adequately performed CT examinations acquired in a timely fashion. In patients with multiple trauma, the "panscan" (CT of the head, neck, chest, abdomen, and pelvis) has become the necessary step to enable physicians to diagnose and ascertain the severity of the injuries and to determine the order in which these should be treated. CT is superior to clinical evaluation and diagnostic peritoneal lavage for diagnosing important abdominal injuries (12,13). Thus, the fundamental role of the trauma radiologist in this management algorithm cannot be overemphasized. Trauma centers designated by the American College of Surgeons as level I are required to have CT available at all times. In many such centers, state-of-the-art CT scanners have been installed in the vicinity of the emergency or trauma room. More recently, the incorporation of CT into the early resuscita-

tive efforts by installing scanners inside modern trauma bays, where patients are assessed initially and triaged, has been proposed (14).

Shortly after its introduction into clinical practice nearly 3 decades ago, CT redefined our understanding of the appearance and importance of abdominal organ injuries (15). Subsequently, helical CT technology improved the accuracy and expanded the applications of CT imaging (16,17). Recent hardware and software developments, especially multidetector technology (18,19), have further potentiated the methods used to evaluate the polytrauma patient in multiple facets: diagnostic capability, speed, and patient safety. In the remaining sections of this article we will review the current elements of CT technique that are relevant today for evaluating blunt abdominal trauma, including some that remain somewhat controversial at this time, and describe the most important CT signs of trauma in the various organs. Because conservative nonsurgical therapy is preferred for all but the most severe injuries affecting the solid viscera (20–23), we emphasize the findings that are indications for direct therapeutic intervention.

Multidetector CT Technique

Optimizing the CT technique for abdominal trauma requires consideration of several aspects pertaining to image acquisition and interpretation. Most important are proper use of contrast material and acquisition of the appropriate number (with correct timing) of phases of contrast material enhancement. The flexibility and speed of modern multidetector scanners mandate that a much more thoughtful approach be used when planning the optimal scan for each patient. In addition, as in all applications of CT, the radiation dose delivered should be the minimum necessary so as not to compromise quality or obscure important diagnostic information. Finally, current methods for image reconstruction and postprocessing options should be leveraged to maximize diagnostic efficiency and accuracy.

Use of Contrast Material

All trauma patients should receive a bolus of intravenous contrast material, typically 100–150 mL (350 mg of iodine per milliliter, total iodine load of 35–52.5 g) ideally injected at a rate of 3–5 mL/sec through an 18- or 20-gauge cannula located in a large peripheral vein. Use of a dual-syringe power injector allows the contrast material to be followed immediately by 30–70 mL of saline solution as a chasing bolus, also at a rate of 3–5 mL/sec. Although a single bolus injection method is used widely, a split bolus technique has been proposed (24). With a split bolus, a single acquisition is performed for evaluation of the integrity of the abdominal viscera and renal collecting system, thereby decreasing the number of CT series acquired and minimizing radiation dose (24). Oral contrast material for evaluating patients is no longer administered at most large trauma centers in the setting of blunt trauma (25–27).

Multiphasic Imaging

An ideal trauma CT protocol would be one that maximizes detection of important abdominal injuries while at the same time minimizing patient risks. Multidetector scanners offer the possibility to acquire images at multiple phases of enhancement. Thus, numerous combinations of enhancement phases have been advocated, and data continue to accumulate that support various approaches.

At our institution, we use a 64-detector CT scanner for all trauma patients. A typical multitrauma CT protocol includes portal venous phase images of the abdomen and pelvis, acquired 65–80 seconds after the beginning of intravenous contrast material administration. Although peak enhancement in each solid organ occurs at slightly different points in time, the portal venous phase offers a good compromise to maximize detection of parenchymal injuries. Longer delays (75–80 sec) are advised when a CT scanner with 16 (or more) detectors is used. In addition to the portal venous phase series, delayed phase (5–10 minutes after intravenous contrast material administration) images are necessary in patients with in-

Figure 1

a. b. c.
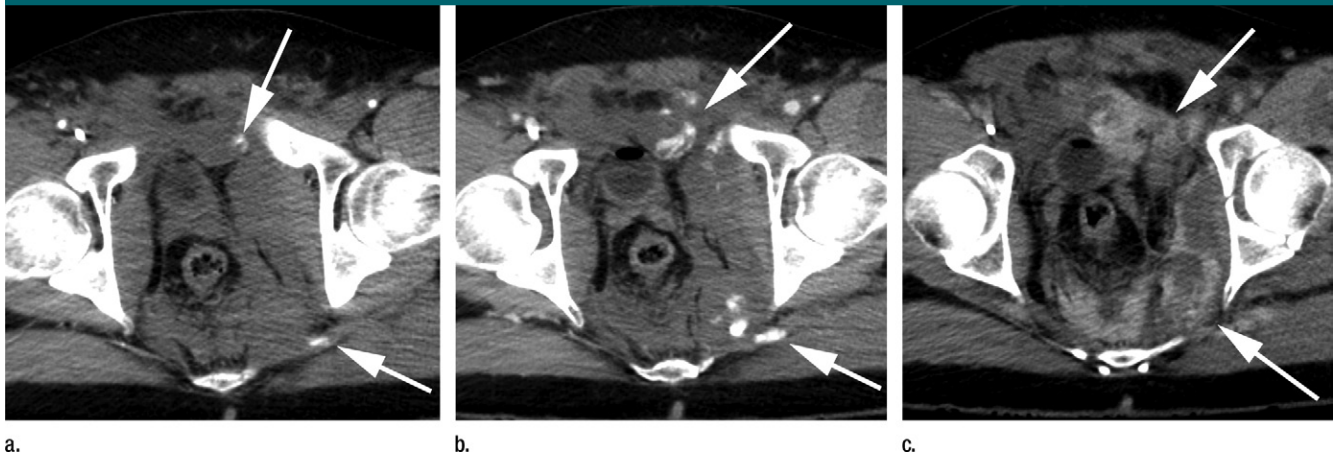
Figure 1: Axial CT images in a 25-year-old man who fell from a second floor. **(a)** Arterial phase image demonstrates foci of active hemorrhage in the pelvis (arrows). Presence of this finding in the arterial phase of image acquisition signifies an arterial source of hemorrhage. **(b)** Portal venous phase image demonstrates enlargement of areas of hemorrhage (arrows), an expected finding in cases of active hemorrhage. **(c)** Delayed phase image demonstrates further enlargement of areas of hemorrhage (arrows). Overall, degree of hemorrhage and increase in size over the three phases of image acquisition are indicative of a large arterial bleed. Note higher image noise in **a** and **c**, as compared with **b**, due to lower radiation dose delivered in **a** and **c**.

Figure 2

Figure 2: CT cystography in a 52-year-old man who was in a motorcycle accident. Coronal reformation image reveals extraperitoneal bladder injury with extraluminal contrast material leaking from the bladder into the extraperitoneal space inferior to the bladder (arrow).

juries suspected or confirmed on the portal venous phase images. This delayed series increases the sensitivity for detecting injuries of the urinary tract, as well as further characterizing solid visceral organ injuries that involve the vasculature (28–30). Selective (rather than routine) acquisition of the delayed phase series is recommended to limit the amount of radiation delivered (31). This approach demands that the radiologist be available to review the portal venous phase images at the CT console or interpreting workstation while the patient is still on the CT scanner table. The specific indications for obtaining the delayed series vary between institutions. At our institution, presence of any sign of intraabdominal traumatic injury prompts the decision to acquire delayed images.

While not yet in widespread practice, there is growing evidence that supports the addition of an arterial phase series (25–30 seconds after injection) of the abdomen and/or pelvis in selected trauma patients: those with severe mechanisms of injury and those who have a displaced fracture of the pelvic ring on the portable radiograph of the pelvis obtained at the time of admission (20,32–35). Arterial phase images facilitate detection of trauma to the major vessels and demonstrate vascular injuries of the solid organs that are not apparent on portal venous or delayed phase images. In the pelvis, arterial phase images help characterize foci of active extravasation as arterial in origin (as opposed to venous or osseous) (34,35) (Fig 1). With the speed afforded by 64-detector scanners (and beyond), these CT angiograms can be readily integrated into comprehensive protocols that use a single bolus of intravenous contrast material. In fact, a whole-body CT angiogram (circle of Willis to symphisis pubis or beyond) is possible and has been advocated for patients with severe polytrauma (36,37).

Finally, patients suspected of having a bladder injury should undergo CT cystography. A proper CT cystographic examination requires that at least 300–400 mL of diluted water-soluble contrast material (solution of 40 mL of contrast material and 360 mL of normal saline) be instilled by means of drip infusion through a Foley catheter (38,39) (Fig 2). In severe polytrauma, the CT cystogram may be acquired simultaneously with the delayed phase scan of the abdomen and pelvis so as to limit the radiation dose. However, full active distention of the bladder through a Foley catheter is still required.

Radiation Dose

Given that the trauma population often involves young, otherwise healthy patients, it is important to balance the risk of radiation exposure with the benefits of an examination that helps answer all the clinically important ques-

tions. An incomplete or suboptimal study may lead to repeat or additional tests, ultimately adding to the total radiation dose. Thus, every effort should be made to decrease the radiation delivered while not compromising the diagnostic capability of the CT study.

Several techniques may be used to accomplish this task (40). The number of phases acquired, beyond the routine portal venous phase, should be carefully selected. Thus, for instance, a delayed series should be limited to patients with abnormalities seen on the portal venous phase images. Automated dose modulation is another method used routinely with modern CT scanners to decrease radiation exposure. With automated dose modulation, the radiation delivered fluctuates during the CT acquisition (by means of modulation of the tube current), on the basis of patient size determined in the longitudinal (z-axis) and axial (in-plane) planes (41). For those series with inherent high contrast, such as CT angiograms, and those used to characterize (rather than help detect) injuries, such as delayed series, radiation dose settings should be adjusted to yield a decrease in tube current and correspondingly higher image noise (Fig 1).

Image Processing

The ability to acquire submillimeter isotropic or near-isotropic data sets with modern multidetector scanners affords multiple image reconstruction and processing options. An initial important consideration pertains to the selection of section thickness for image reconstruction. A common practice is to reconstruct the acquired thin (submillimeter) sections to yield thicker sections (2.5–5.0 mm) in the axial, coronal, and sagittal planes, to facilitate image interpretation. These routine orthogonal plane reformations have been demonstrated to improve the accuracy for diagnosing certain acute injuries, especially of the diaphragm and spine (39,42–44). Thinner sections of all series in the various planes would lead to image overload, with patient data sets composed of thousands of images in the typical multiphasic acquisition of multiple regions of the body. This approach also weighs the radiation exposure implica-

tions, since reconstructing thicker data sets with diagnostically acceptable signal to noise requires lower radiation dose than do thinner data sets, if image noise is to be maintained.

CT Findings of Abdominal Trauma

Hemoperitoneum and Free Peritoneal Fluid

Injuries to solid and hollow viscera commonly have associated hemoperitoneum. A careful analysis of the attenuation of the hemorrhagic fluid helps identify the source of bleeding. Nonclotted blood (typical attenuation of 30–45 HU) tends to flow freely between contiguous peritoneal recesses, following gravity, and may eventually fill the cavity completely. Blood located adjacent to the source of the hemorrhage is typically partially clotted and tends to be higher in attenuation (45–70 HU); this finding is termed the *sentinel clot sign* (45). This sign is most helpful when the bleeding site is not readily apparent or in the setting of injuries to multiple organs, where one or several organs could be the source. Although the volume of hemoperitoneum may be estimated roughly by searching for fluid in the various spaces (46), the rate of bleeding and the presence of active extravasation have a more direct effect on patient care decisions. A large hemoperitoneum does not mandate laparotomy (46). Occasionally, the attenuation values of hemoperitoneum may be less than 20 HU (47). This may occur, for example, in patients with preexistent anemia. Thus, in some patients, hemoperitoneum may be difficult to distinguish from simple ascites, bile, extraluminal fluid originating from a small bowel perforation, or intraperitoneal urine from a ruptured bladder.

The finding of free intraperitoneal fluid in the absence of direct signs of solid or hollow visceral injury poses particular challenges, particularly in male patients. A thorough search for additional direct signs of organ injury is critical in these cases. In female patients of reproductive age, isolated free fluid in the pelvis can be explained by

the normal menstrual cycle. In male patients, the question is often raised regarding the clinical importance of free fluid alone and whether laparotomy (or laparoscopy) should be recommended. In the late 1990s, studies suggested that isolated free intraperitoneal fluid in male patients should be assumed to arise from a perforated hollow viscus and, therefore, that laparotomy was required (48). More recent work with newer generations of CT scanners has shown a higher sensitivity for detecting small amounts of free peritoneal fluid. This has led to a more conservative approach for management (49). Results of studies by Drasin et al (50) and Yu et al (51) showed that small pockets of low-attenuation fluid (10–15 HU) can be found in the pelvis of 3%–5% of male blunt trauma patients, in the absence of any hollow or solid organ injury (Fig 3). One study found a trend for increased frequency of free fluid as an isolated finding in patients who receive higher volumes of intravenous fluid for resuscitation (50).The current recommendation is to admit these patients for close clinical observation and, if necessary, repeat CT without immediate surgical intervention (52).

Splenic Injuries

The spleen is the most commonly injured organ in blunt trauma. Given the role of the spleen in immune function and the potential for overwhelming infection after splenectomy (53), splenic preservation after trauma is the current standard of care. Avoiding splenectomy (surgically, with subtotal resection, or splenorrhaphy when possible) or nonsurgically, with observation or endovascular interventions, has become a key goal in trauma care. Currently, the success rate of nonsurgical therapy varies between 80% and 90% (54) Thus, accurate identification of injuries that may necessitate surgical or angiographic intervention is of critical importance (21,55,56). Management decisions in cases of acute splenic injury are based on patient demographics (especially age) and clinical signs and symptoms and often rely on the splenic injury grade as determined on the basis

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Figure 3

a.

b.
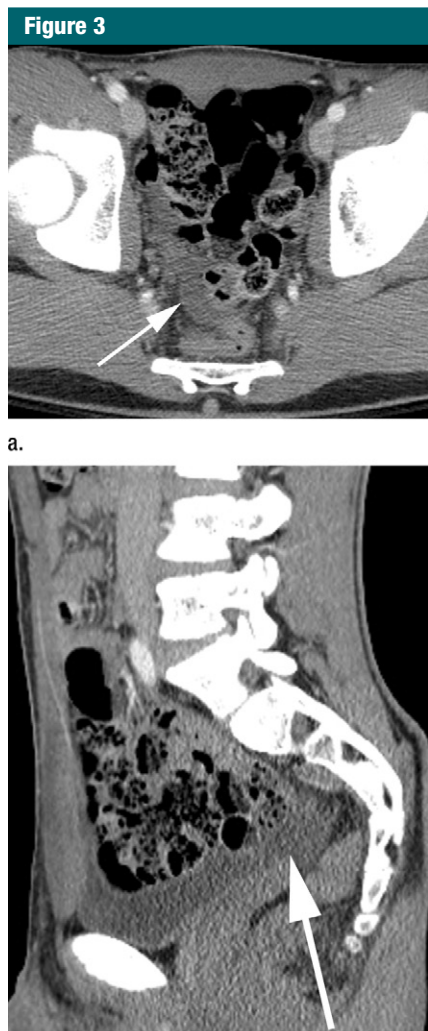
Figure 3: CT images in a 20-year-old man who was a passenger in a motor vehicle accident. **(a)** Axial contrast agent–enhanced image and **(b)** sagittal reformation demonstrate a small amount of low-attenuation free fluid (measured mean attenuation, 8 HU) in the pelvis (arrow). The remainder of the CT study showed no evidence of solid or hollow visceral organ injury. The patient was admitted for observation and released the next day with no intervention.

Table 1

AAST Splenic Injury Scale (1994 Revision)

Grade and Type of Injury	Description of Injury
I	
Hematoma	Subcapsular, <10% surface area
Laceration	Capsular tear, <1 cm parenchymal depth
II	
Hematoma	Subcapsular, 10%–50% of surface area or intraparenchymal hematoma < 5 cm in diameter
Laceration	1–3 cm Parenchymal depth; does not involve trabecular vessels
III	
Hematoma	Subcapsular hematoma, >50% surface area or expanding; ruptured subcapsular or intraparenchymal hematoma; intraparenchymal hematoma > 5 cm or expanding
Laceration	>3 cm Parenchymal depth or involves trabecular vessels
IV	
Laceration	Laceration involves segmental or hilar vessels, producing major devascularization (>25% of spleen)
V	
Laceration	Completely shattered spleen
Vascular	Hilar vascular injury that devascularizes spleen

Source.—Reference 57.

Note.—Increase by one grade (up to grade III) for multiple injuries.
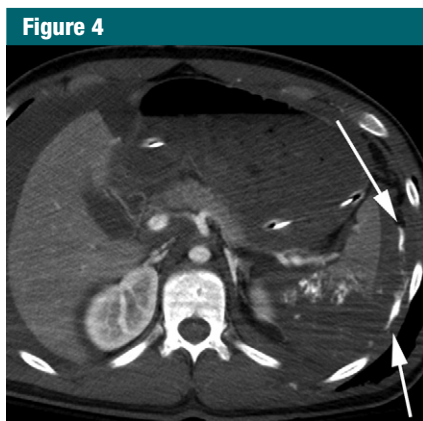
Figure 4

Figure 4: Axial contrast-enhanced CT image in a 19-year-old man who was in a motor vehicle collision demonstrates large splenic laceration with active hemorrhage seen emanating from the splenic injury into the peritoneal cavity (arrows). Note large degree of hemoperitoneum related to this grade V splenic injury. Patient underwent emergent splenectomy.

of CT results. The traditional CT-based splenic injury scale system was developed by the American Association for the Surgery of Trauma (AAST) and accounts for the size and location of splenic lacerations and hematomas (Table 1) (57) (Fig 4). Higher grade injuries (AAST grade III and higher) more often require surgical therapy. On CT images, splenic lacerations and hematomas are readily identified as linear defects or relatively hypoattenuating geographic areas in the parenchyma.

However, the use of such CT-based splenic injury grading systems has been found to be a relatively poor predictor of patient outcome and, specifically, has been shown to be a poor predictor of the eventual success of nonsurgical management (58,59).

In an effort to improve the ability of CT to help predict successful nonsurgical management in splenic trauma and, ultimately, to improve patient care, several additional CT features of splenic trauma are important considerations. The amount of hemoperitoneum has been shown to predict the eventual success of nonsurgical management; patients with smaller degrees of hemoperitoneum have higher rates of successful nonsurgical management (60). In addition, the presence of active hemorrhage and/or contained vascular injuries (pseudoaneurysms and arteriovenous fistulae) increases the risk of failed nonsurgical management (61). Active hemorrhage is identified as a contrast material blush or focal area of hyperattenuation in or emanating from the injured splenic parenchyma. In contradistinction to a contained vascular injury in which the

Table 2

Multidetector CT–based Splenic Injury Grading System

Injury Grade	Description of Injury
I	Subcapsular hematoma < 1 cm thick; laceration < 1 cm parenchymal depth; parenchymal hematoma < 1 cm diameter
II	Subcapsular hematoma 1–3 cm thick; laceration 1–3 cm parenchymal depth; parenchymal hematoma 1–3 cm diameter
III	Splenic capsular disruption; subcapsular hematoma > 3 cm thick; laceration > 3 cm parenchymal depth; parenchymal hematoma > 3 cm diameter
IVA	Active intraparenchymal or subcapsular splenic bleeding; splenic vascular injury (pseudoaneurysm or arteriovenous fistula); shattered spleen
IVB	Active intraperitoneal bleeding

Note.—Adapted and reprinted from reference 62.

Table 3

AAST Liver Injury Scale (1994 Revision)

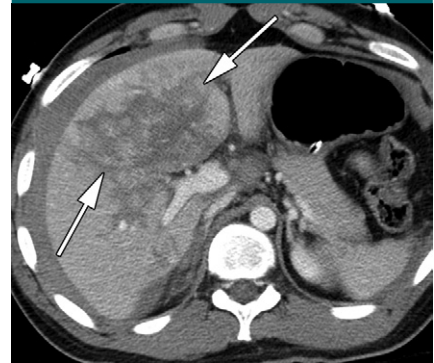| Grade and Type of Injury	Description of Injury
I	
Hematoma	Subcapsular, <10% surface area
Laceration	<1 cm In depth
II	
Hematoma	Subcapsular, 10%–50% of surface area; intraparenchymal hematoma <10 cm in diameter
Laceration	1–3 cm In depth or <10 cm in length
III	
Hematoma	Subcapsular, > 50% surface area or expanding; ruptured subcapsular or parenchymal hematoma; intraparenchymal hematoma >10 cm or expanding
Laceration	>3 cm Parenchymal depth
IV	
Laceration	Parenchymal disruption involving 25%–75% of hepatic lobe or one to three Couinaud segments in a single lobe
V	
Laceration	Parenchymal disruption involving >75% of hepatic lobe or more than three Couinaud segments in a single lobe
Vascular	Juxtahepatic venous injuries (ie, retrohepatic vena cava and/or central major hepatic veins)
VI	
Vascular	Hepatic avulsion

Source.—Reference 57.

Note.—Increase by one grade (up to grade III) for multiple injuries.

Figure 5

Figure 5: Axial contrast-enhanced CT image in a 27-year-old man who was in a high-speed rollover motor vehicle collision shows grade IV liver injury involving majority of right lobe (arrows). Note also the perihepatic hemoperitoneum.

initially identified contrast material blush is seen to wash out on subsequent delayed phase images, the hyperattenuation of active hemorrhage persists and grows larger with time on a delayed phase study. Thus, delayed phase image acquisition is useful for definitive characterization of vascular splenic injury as active hemorrhage or contained vascular injury (28,61). Recently, a multidetector CT–based scale system that includes contained vascular injuries and active bleeding as part of the grading criteria (Table 2) has been proposed to improve the accuracy of predicting the need for intervention, as compared with the traditional AAST scale (62). However, based on the observation that not all vascular injuries of the spleen are identified on the combination of portal venous and delayed phase images, some advocate routine acquisition of an additional arterial phase series during the CT examination of the abdomen (20). Further study related to the use of arterial phase imaging in abdominal trauma on the basis of this work is ongoing, and this area deserves further inquiry.

Hepatic Injuries

Hepatic injuries are common and are associated with important complications. Similar to the spleen, the majority of blunt hepatic injuries are now successfully managed nonsurgically (23,63,64). Timely and accurate diagnosis and characterization of liver trauma is important in guiding clinical management decisions (65,66). Similar to the aforementioned approach to splenic trauma imaging, the AAST liver injury scale (Table 3) is commonly applied when assessing the severity of the acute hepatic injury (57,67). The liver injury scale is based on the presence, location, and size of liver lacerations and hematomas (Fig 5), as well as the presence of more extensive tissue maceration or devascularization in higher-grade injuries.

Lacerations are the most frequently identified injury pattern in liver trauma and are identified as predominately linear areas, often with a branching pat-

tern, of relative hypoattenuation (68). Injuries affecting the bare area in the superomedial aspect of the liver posteriorly, the portion not covered by peritoneal reflection, may cause large retroperitoneal hematomas (69). In addition to the number and size of lacerations, the AAST liver injury scale considers the size and location of hematomas, which may be intraparenchymal and appear as ill-defined areas of relative hypoattenuation in the liver parenchyma or subcapsular and appear as crescentic hypoattenuating regions compressing the underlying liver. However, although reports have been mixed, the application of such a CT-based scheme established according to the AAST liver injury scale has limitations in the ability to guide subsequent management decisions or predict complications related to liver injuries, similar to imaging of splenic trauma (65,70). Additional imaging findings that have been found to be useful in guiding clinical management decisions include *(a)* extension of the injury to involve the major hepatic veins, which usually requires surgery to control ongoing hemorrhage; *(b)* the presence of active bleeding into the peritoneal cavity, which can usually be treated with endovascular intervention (65); and *(c)* the presence of a large hemoperitoneum (71).

The growing trend toward nonsurgical management of hepatic injuries has increased the relevance and frequency of delayed complications such as bile leaks, biliary strictures, hepatic abscess, delayed hemorrhage, and other vascular complications. Delayed (or continued) hemorrhage can occur secondary to the formation of pseudoaneurysms, which are inherently unstable and can rupture through a laceration into the peritoneal cavity or the biliary system, resulting in hemobilia (32). While less common, hepatic abscesses can occur in patients who sustain high-grade injuries. Bile leaks and bilomas must be suspected in all patients with severe liver injury and are seen on CT images as low-attenuating fluid collections, often enlarging over time. Hepatobiliary scintigraphy is a simple and accurate test to detect biliary leaks and bilomas (72). The complications of biliary injuries and pseudoan-

eurysm formation in liver trauma have been reported to be highly correlated and are postulated to be related to the erosive properties of bile (73,74).

Bowel and Mesenteric Injuries

Although injuries to the hollow viscera and mesentery are rare, occurring in approximately 5% of patients with severe blunt abdominal trauma (4,75), one of the most essential tasks for the emergency radiologist is to recognize the often subtle CT signs of bowel trauma. Delays in diagnosis as short as 8–12 hours increase the morbidity and mortality from peritonitis and sepsis (76). At least one-half of injuries to hollow viscera involve the small bowel, followed in frequency by the colon and stomach (77). The segments affected most commonly are the proximal jejunum (distal to the ligament of Treitz) and the distal ileum (proximal to the ileocecal valve). Patients with a Chancetype vertebral fracture and large abdominal wall hematoma have a higher risk of injury to the bowel or mesentery (77–80).

A variety of signs help diagnose bowel and mesenteric injuries with CT. The importance of each individual finding varies. Unfortunately, the more specific signs are not highly sensitive, and the more sensitive signs are not highly specific (Table 4). However, the presence of a combination of these findings increases the likelihood of a clinically important injury (ie, one that necessitates surgical management). The specific signs of bowel injury include transection of the wall with focal discontinuity, extraluminal oral contrast material (on the rare occasions when it is administered), pneumoperitoneum (Fig 6), and pneumoretroperitoneum. Specific signs of mesenteric trauma include mesenteric hematoma, peritoneal extravasation of intravenous contrast-enhanced blood, and abrupt termination or unequivocal irregularity of the walls of mesenteric vessels. The less specific (but more sensitive) CT signs of bowel trauma include unequivocal focal wall thickening (Fig 6), abnormal bowel wall enhancement, ill-defined increased attenuation (stranding) of the mesentery,

and free intraperitoneal fluid (Fig 6). Studies that used various generations of CT scanners report a sensitivity that varies between 70% and 95% and a specificity that varies between 92% and 100% for the diagnosis of bowel and mesenteric injuries (25,78–81).

Extraluminal gas is a highly suggestive, but not pathognomonic, sign of bowel perforation. The amount of free gas varies widely. CT images should routinely be reviewed with lung or bone window settings, in addition to the routine soft-tissue settings. This approach facilitates the detection of small gas collections. It is also important to review carefully all phases acquired because, on occasion, pneumoperitoneum may appear only on delayed images. Causes of pneumoperitoneum without bowel trauma include intraperitoneal rupture of the urinary bladder with an indwelling Foley catheter, massive pneumothorax, barotrauma, benign pneumoperitoneum (eg, as observed in some patients with systemic sclerosis) and the occasional diagnostic peritoneal lavage. "Pseudopneumoperitoneum," air confined between the abdominal wall and the parietal peritoneum, is another potential cause of a false-positive diagnosis of bowel rupture. This finding may be seen with extraperitoneal rectal injuries, rib fractures, pneumothorax or pneumomediastinum (81). Although on CT images, the appearance may resemble pneumoperitoneum, most patients with true pneumoperitoneum have collections of gas located deeper in the peritoneal cavity. However, the majority of patients with proved bowel perforations do not have free gas on CT images. This occurs because the perforation seals spontaneously, because developing ileus prevents passage of gas into the abdominal cavity, or because small gas collections may rapidly be reabsorbed through the peritoneal lining.

Unequivocal localized thickening or abnormal enhancement of a bowel loop or segment are highly suggestive of a surgically important injury, such as a contusion, hematoma, ischemia secondary to mesenteric vascular trauma, or perforation. The likelihood of a focal bowel abnormality representing an in-

jury that requires surgical intervention increases when found in association with pockets of fluid in the adjacent mesentery or free fluid in the peritoneal cavity (82). Diffuse bowel wall thickening is usually not a result of direct trauma but more likely related to the hypoperfusion complex ("shock bowel") (83). Although the vast majority of bowel injuries have associated abnormalities in the mesentery (Fig 6), the converse is not always true. Mesenteric injuries can be an isolated finding on CT images, and these findings include peritoneal active extravasation of contrast-enhanced blood, mesenteric rent with internal hernia, beading or abrupt termination of the mesenteric vessels, and mesenteric hematoma (80). Small isolated mesenteric hematomas are not always an indication for immediate surgery and can be treated with observation alone. Larger hematomas and mesenteric vascular injuries carry the risk of subsequent bowel ischemia and usually require surgical repair, although endovascular therapy with coil embolization can be attempted in patients with injuries to smaller vessels (80).

Pancreatic and Duodenal Injuries

Blows to the mid–upper abdomen with a steering wheel or bicycle handlebars are the typical mechanisms that injure the pancreas and/or the duodenum, often involving the left hepatic lobe and spleen as well. Patients with pancreatic or duodenal injuries typically complain of epigastric or diffuse abdominal pain and vomiting. The diagnosis of pancreatic injuries on CT can be problematic. The sensitivity of multidetector CT for detection of pancreatic injuries has been reported between 70% and 95% (10,84–87). In fact, the injured pancreas may appear normal on CT images, particularly in the first 12 hours after a trauma injury (85). Indirect signs of pancreatic injury include fluid in the peripancreatic fat or in the plane separating the pancreas from the splenic vein and thickening of the left anterior renal fascia. If the admission CT image shows a normal pancreas but the patient subsequently develops abdominal pain, a repeat CT study obtained 24–48 hours

Table 4

Sensitivity and Specificity of Various CT Signs of Bowel Injury

Sign	Sensitivity (%)	Specificity (%)
Bowel wall discontinuity	5–10	100
Extraluminal oral contrast material	8–15	100
Extraluminal air	30–60	95
Focal bowel wall thickening	55–75	90
Abnormal bowel wall enhancement	10–15	90
Mesenteric infiltration ("stranding")	70–77	40–90
Free peritoneal fluid	90–100	15–25

Source.—References 25, 80–83.

Figure 6

a.

b.

c.
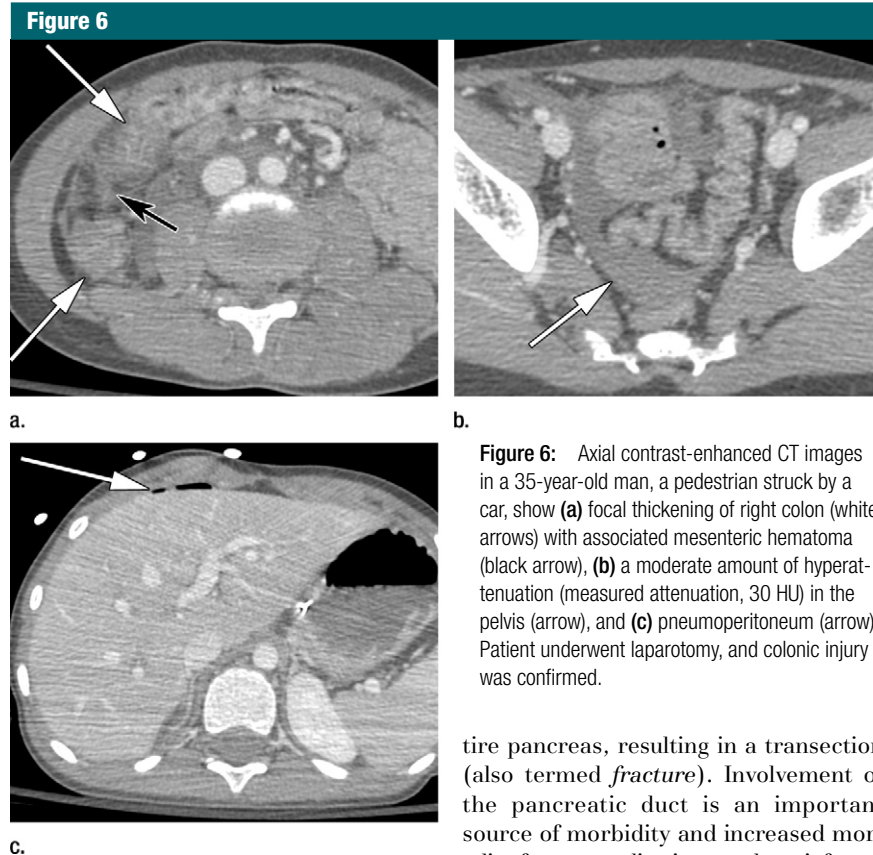
Figure 6: Axial contrast-enhanced CT images in a 35-year-old man, a pedestrian struck by a car, show **(a)** focal thickening of right colon (white arrows) with associated mesenteric hematoma (black arrow), **(b)** a moderate amount of hyperattenuation (measured attenuation, 30 HU) in the pelvis (arrow), and **(c)** pneumoperitoneum (arrow). Patient underwent laparotomy, and colonic injury was confirmed.

later may show an injury not evident initially (84).

The neck and body of the gland are the most common sites of injury. Pancreatic injuries may be classified as contusion, laceration, or transection. Contusions are focal areas of low attenuation or enlargement (Fig 7). Lacerations may be superficial or extend through the entire pancreas, resulting in a transection (also termed *fracture*). Involvement of the pancreatic duct is an important source of morbidity and increased mortality from complications such as infected pseudocyst, abscess, fistulae, or sepsis (84–86). The depth of a laceration is correlated with the likelihood of pancreatic ductal injury: involvement of more than 50% of the thickness usually causes ductal injury (86). MR pancreatography is a valuable noninvasive method to establish integrity of the main duct (88), but endoscopic retrograde pancreatography remains as the standard of reference and serves as a means for endo-

scopic therapy (eg, stent placement) in some patients as well.

Isolated duodenal injuries are uncommon. CT findings are similar to those for injuries involving other segments of the gastrointestinal tract and include focal wall discontinuity, wall thickening, periduodenal fluid, and extraluminal gas in the retroperitoneum (89). Duodenal hematomas typically occur in younger patients: Blood accumulates in the submucosal or subserosal layer of the otherwise intact duodenal wall. Gastric outlet obstruction is a common complication of duodenal hematomas, particularly in the early stages after the injury. The management of isolated duodenal hematomas is conservative (90,91).

Surgical management of duodenal lacerations hinges on the extent and severity of the duodenal injury, as well as the involvement of the adjacent vasculature, biliary tree, and pancreas (10,90,91). Uncomplicated duodenal lacerations are repaired by means of primary surgical closure, known as duodenorrhaphy, while more complex injuries require reconstructive procedures. Pancreaticoduodenectomy is reserved for patients with severe combined duodenal and pancreatic head injuries (10).

Hypoperfusion Complex

CT findings provide a general overview of the hemodynamic status of the traumatized patient and help detect persistent hypovolemia after initial resuscitation with administration of crystalloid fluids. The constellation of findings that has been termed *hypoperfusion complex* includes a collapsed infrahepatic inferior vena cava with flattening of the renal veins, decreased caliber of the aorta, diffusely thickened and hyperenhancing small bowel (shock bowel) (Fig 8), increased enhancement of the kidneys and adrenals, decreased enhancement of the spleen, and pancreatic enlargement with peripancreatic and retroperitoneal edema. CT findings of the hypoperfusion complex were originally described in children (92), in whom the prognosis is very poor, but can also be seen in adults (83,93). Diffuse bowel wall thickening and edema can also be caused by fluid overload. In this situa-

tion, the inferior vena cava and hepatic veins appear distended, and the liver may demonstrate a heterogeneous pattern of enhancement ("nutmeg" appearance) as well as a concentric halo of low attenuation ("collar") around the portal veins (94), while the other abdominal organs and vessels have a normal appearance.

Urinary Tract and Adrenal Injuries

A motor vehicle collision is the most common mechanism responsible for injuries to the kidneys and urinary tract. The presence of hematuria (gross or microscopic) after abdominal trauma is a good predictor of the presence of a urinary tract injury (95–97). Similar to what exists for liver and spleen, an AAST grading system is applied to classify the severity of renal trauma (Table 5) and takes into account the size and location of renal lacerations and hematomas (97). The majority of traumatic renal injuries are treated conservatively with observation alone (96,97). Therapeutic interventions (endovascular, urologic, or, rarely, surgical) are reserved for disruptions of the collecting system and for vascular injuries. CT findings correlate well with the AAST classification. According to the AAST grading system, grade IV injuries include lacerations that involve the renal collecting system. Delayed CT images are necessary to determine the integrity of the collecting system (see Multidetector CT Technique) and allow detection of leakage of opacified urine into the perinephric space (Fig 9). Urinomas should be suspected in all cases in which perinephric fluid is identified on portal venous phase images (95,96). Injuries to the extrarenal collecting system, such as disruption of the ureteropelvic junction, are uncommon but can occasionally be seen in cases of deceleration trauma. Avulsions of the renal pedicle are included in the higher grades of injury (grade V), and carry a high risk of ongoing hemorrhage and acute thrombosis, with complete devascularization of the kidney. On CT images, pedicle avulsions are characterized by very poor or absent enhancement of the kidney. Vascular injuries that can be demon-

Figure 7

a.

b.
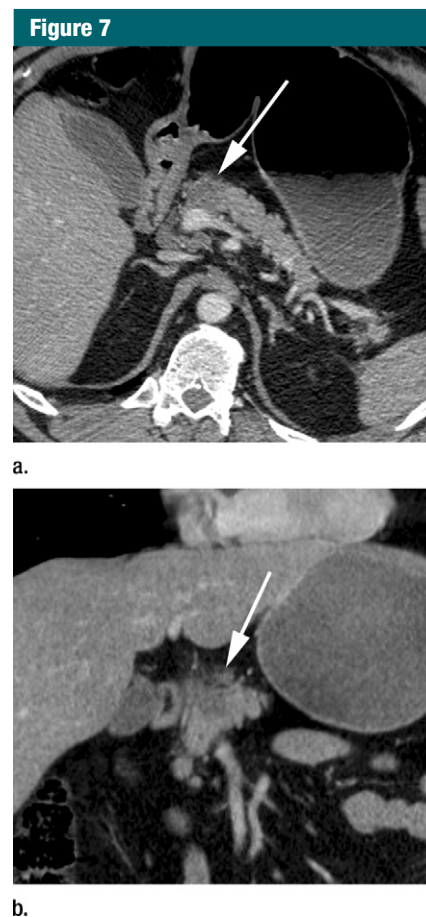
Figure 7: CT images in a 53-year-old man who was in a motor vehicle collision. **(a)** Axial contrast-enhanced image and **(b)** coronal reformation show pancreatic contusion (arrow, **a**) as evidenced by a focal region of hypoattenuation. There is also mild peripancreatic hemorrhage (arrow, **b**).

strated well on CT images include dissection, pseudoaneurysms, and arteriovenous fistulas and may result in segmental renal ischemia or infarction.

Ruptures of the urinary bladder usually occur as a complication of pelvic fractures, especially in patients who have a distended bladder at the time of the impact. Thus, patients with pelvic fractures or gross hematuria should be examined with CT cystography (38,39), to assess integrity of the urinary bladder (see Multidetector CT Technique) (Fig 2). Bladder ruptures can be intraperitoneal, extraperitoneal, or combined intra- and extraperitoneal. In the case of intrapertitoneal injuries, the contrast

Figure 8

a.   b.
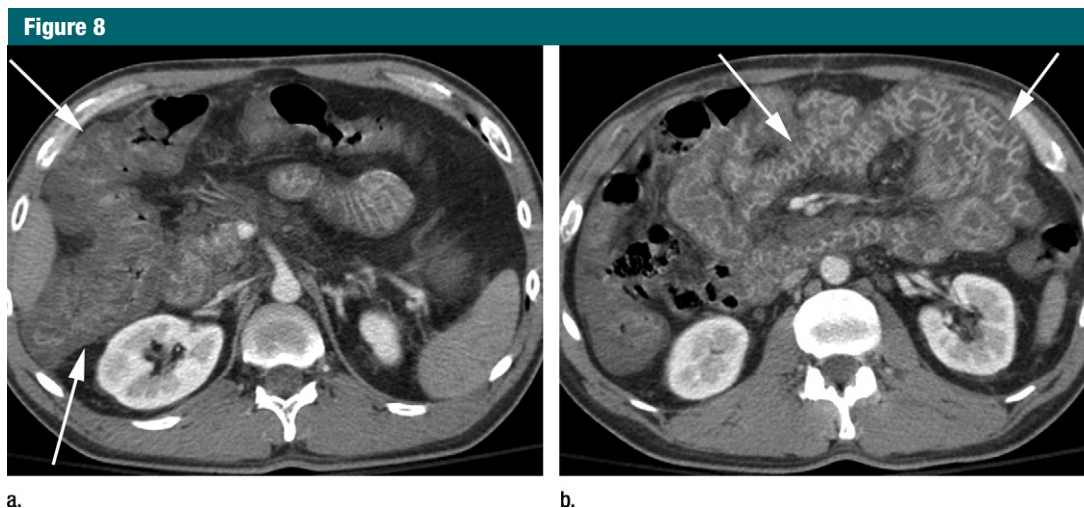
Figure 8:   Axial contrast-enhanced CT images in a 28-year-old man who was involved in a motorcycle accident that resulted in multiple extremity fractures and soft-tissue hematomas show **(a)** diffuse thickening of the wall of the right colon (arrows) and **(b)** diffuse thickening and diffuse mucosal hyperenhancement of the small bowel (arrows). Note also collapsed inferior vena cava and hyperenhancement of adrenal glands. These findings are characteristic of shock bowel, related to hypoperfusion complex.

Table 5

AAST Kidney Injury Scale

Grade and Type of Injury	Description of Injury
I	
Contusion	Microscopic or gross hematuria, with normal urologic studies
Hematoma	Subcapsular nonexpanding, without parenchymal laceration
II	
Hematoma	Nonexpanding perirenal hematoma confined to renal retroperitoneum
Laceration	<1 cm Parenchymal depth of renal cortex, without urinary extravasation
III	
Laceration	>1 cm Parenchymal depth of renal cortex, without collecting system rupture or urinary extravasation
IV	
Laceration	Parenchymal laceration extending through renal cortex, medulla, and collecting system
Vascular	Main renal artery or vein injury, with contained hemorrhage
V	
Laceration	Completely shattered kidney
Vascular	Avulsion of renal hilum, which devascularizes kidney

Source—Reference 98.

Note.—Advance one grade for multiple injuries to the same organ.

material flows outside of the bladder lumen to outline peritoneal structures, such as the bowel and mesentery. In extraperitoneal ruptures, which are more common (accounting for 80%–90% of cases), the contrast material extends into the perivesical space and other more distant extraperitoneal locations (98). This distinction between an intraperitoneal and an extraperitoneal rupture is important and has direct therapeutic implications, because intraperitoneal ruptures require surgical repair and extraperitoneal ruptures can typically be treated conservatively, without surgery (98).

The adrenal glands are injured in approximately 2% of patients who undergo blunt abdominal trauma (99). Major forces are required to injure the adrenals. Not surprisingly, traumatic adrenal hemorrhage is usually accompanied by injuries in other upper abdominal organs, especially the liver. Approximate distribution of adrenal hemorrhage secondary to blunt trauma is the right adrenal in 75% of cases, the left adrenal in 15% and both adrenals in 10% (99). Unilateral adrenal hematomas usually resolve spontaneously, without any sequelae. Bilateral hemorrhage occasionally manifests as adrenal insufficiency. On CT images, adrenal injuries typically manifest as focal hyperattenuating hematomas or as glandular enlargement with ill-defined hemorrhage confined to or extending outside of the gland into the periadrenal or retroperitoneal fat. Differentiation between an adrenal hematoma and a preexistent mass can be difficult and may require a repeat CT (or magnetic resonance imaging) examination, typically 8–10 weeks later.
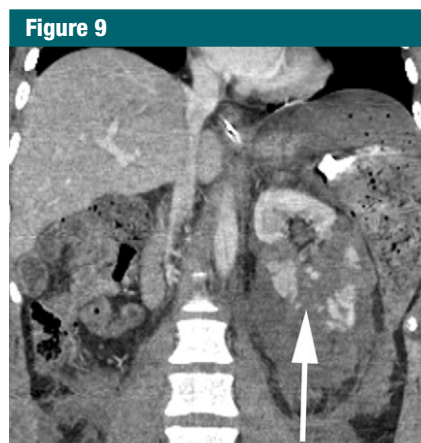
Diaphragmatic Injuries

In blunt trauma, diaphragmatic injuries are caused by a sudden increase in intraabdominal pressure. Injuries to the diaphragm have the potential for im-
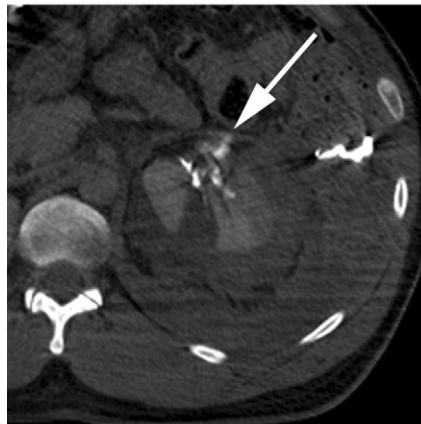
portant morbidity and mortality related to immediate or delayed herniation (and secondary ischemia) of abdominal organs into the thorax (42). While the diagnostic accuracy of CT for detecting diaphragmatic trauma has traditionally been considered low, especially in the case of right-sided injuries, the improvements of multidetector technology (higher spatial resolution, improved multiplanar reformations) allow for improved preoperative diagnoses (43,100–102). These imaging findings include direct visualization of diaphragmatic discontinuity, herniation of abdominal viscera into the thorax, and the collar sign, a waistlike constriction of herniated abdominal contents through a diaphragmatic rent (42,43,100–104) (Fig 10). In patients with a diaphragmatic injury, the herniated viscera adopt an abnormal dependent position along the posterior chest wall. This finding, termed the *dependent viscera sign,* is present if the upper third of the liver, the stomach, or bowel loops are found on CT images to abut the posterior ribs (104) (Fig 10). The use of coronal and sagittal reformations led to the description of two additional variants of the collar sign: the hump sign, in which a rounded portion of the superior liver herniates through the diaphragmatic rent and the band sign, in which the torn free edge of the diaphragm causes a linear indentation in the herniated liver edge (42,43). Recently, the dangling diaphragm sign was described, a conspicuous sign in which the free edge of the injured diaphragm is seen to curl inwards and away from the chest wall (102). Nevertheless, the CT diagnosis of diaphragmatic injury remains challenging, and radiologists should be aware of the imaging findings and diligently review axial and reformatted images.

Major Vascular Injuries and Retroperitoneal Hemorrhage

Injuries to the aorta and other major abdominal and pelvic vessels (inferior vena cava, renal vessels, celiac axis, superior mesenteric vessels, lumbar vessels, and iliac vessels) are uncommon but highly lethal, owing to the rapid rate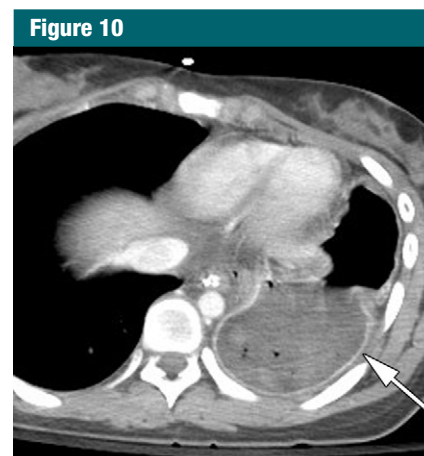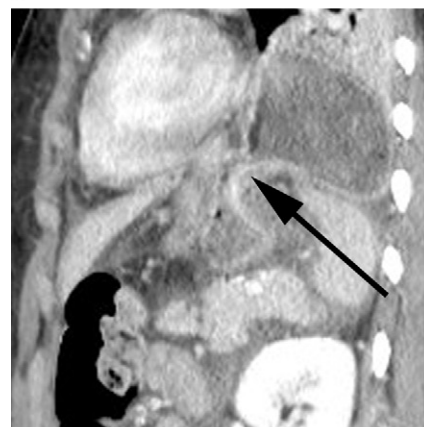 of blood loss into the peritoneal cavity or retroperitoneal spaces. The abdominal aorta may be injured in high-speed automobile accidents, when it can be trapped between a lap belt and the lumbar spine. A timely diagnosis and immediate therapy are necessary to increase the chance of survival. Diagnosis of aortic transection on CT images is obvious when accompanied by a large hematoma or active extravasation of contrast-enhanced blood. More subtle injuries, such as small pseudoaneurysms, intimal flaps, or even throm-

bosis may be very difficult to detect and require a proper CT technique (often with a CT angiographic phase) and a systematic review of the images by the radiologist (105) (Fig 11).

The retroperitoneum can be the source of considerable blood loss that can remain occult to clinical examination and evaluation with FAST (focused assessment with sonography for trauma) (6,7,106). Retroperitoneal he-

Figure 9: CT images in a 34-year-old man who was in a high-speed motor vehicle accident. **(a)** Coronal reformation of portal venous phase CT images shows grade IV renal injury with multiple large renal lacerations (arrow). **(b)** Axial delayed phase CT image shows leakage of contrast-enhanced urine into perinephric space (arrow), caused by an injury to renal collecting system.

Figure 10: CT images in a 40-year-old man who was the driver in a high-speed motor vehicle accident. **(a)** Axial contrast-enhanced image shows herniation of stomach (arrow) into the thoracic cavity secondary to traumatically induced diaphragmatic injury. The stomach abuts the posterior ribs in the left hemothorax—the dependent viscera sign. **(b)** Sagittal reformation shows the collar sign, in which a defect in the diaphragm creates a waistlike constriction of the herniated stomach (arrow).

Radiology

Figure 11

a.

b.

Figure 11: CT images in a 21-year-old man who was in a high-speed motor vehicle collision. **(a)** Axial contrast-enhanced image and **(b)** coronal reformation show intimomedial flap in the abdominal aorta (arrow), consistent with acute aortic injury. There is associated periaortic hemorrhage.

matomas may occur secondary to injuries to major vessels, solid organs, hollow viscera, and/or the skeleton. The pelvis is the most common location of retroperitoneal hemorrhage, often in association with pelvic fractures (107). CT has high sensitivity for detection and determination of the size of a retroperitoneal or pelvic hematoma. However, treatment depends more on the hemodynamic status of the patient, the rate of growth of the hematoma, and the presence of active extravasation of contrast-enhanced blood. Most patients are treated with external fixation and endovascular embolization, with surgery reserved as a life-saving attempt in the most extreme circumstances. CT angi-

ography has been found useful for predicting the need for therapeutic embolization. Foci of active extravasation manifest in the CT angiography phase (34,35) and are good predictors of positive angiographic results and successful embolization (Fig 1).

Conclusion

Multidetector CT technology offers unprecedented imaging capabilities that can be readily applied for optimal evaluation of the polytrauma patient. With the decline in the use of diagnostic peritoneal lavage and the current preference for conservative nonsurgical therapy for all but the most severe injuries affecting the solid abdominal viscera, diagnosis is heavily reliant on the findings of CT studies that are acquired in a timely fashion and adequately performed and the results of which are accurately interpreted. However, to maximize the diagnostic potential of the examination and, at the same time, minimize risks, CT protocols need to be tailored to match the need of each individual patient. The interpreting radiologist should emphasize findings that directly affect patient care, such as presence of active extravasation and injuries to the bowel, pancreas, diaphragm, and vessels.

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