Necrotizing Enterocolitis: Review of State-of-the-Art Imaging Findings with Pathologic Correlation

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Plain abdominal radiography is the current standard imaging modality for evaluation of necrotizing enterocolitis (NEC). Sonography is still not routinely used for diagnosis and follow-up, as it is not widely recognized that it can provide information that is not provided by plain abdominal radiography and that may affect the management of NEC. Like plain abdominal radiography, sonography can depict intramural gas, portal venous gas, and free intraperitoneal gas. However, the major advantages of abdominal sonography over plain abdominal radiography are that it can depict intraabdominal fluid, bowel wall thickness, and bowel wall perfusion. Sonography may depict changes consistent with NEC when the plain abdominal radiographic findings are nonspecific and inconclusive. Thinning of the bowel wall and lack of perfusion at sonography are highly suggestive of nonviable bowel and may be seen before visualization of pneumoperitoneum at plain abdominal radiography. The mortality rate is higher after perforation; thus, earlier detection of severely ischemic or necrotic bowel loops, before perforation occurs, could potentially improve the morbidity and mortality in NEC. The information provided by sonography allows a more complete understanding of the state of the bowel in patients with NEC and may thus make management decisions easier and potentially change outcome.

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Abbreviation: NEC = necrotizing enterocolitis

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Introduction
Necrotizing enterocolitis (NEC) is a common acute abdominal condition seen in the neonatal period. Early diagnosis, which relies on imaging findings, and institution of prompt therapy are essential to limit morbidity and mortality.

The purpose of this article is to review current concepts of the role of imaging in neonates with NEC. We would like to reaffirm the importance of plain abdominal radiography as the current standard imaging modality in this entity and to also emphasize the important role that sonography may play. Sonography is still not routinely used, as it is not widely recognized that it can provide information that is not depicted on radiographs and that may indeed affect management of patients with NEC.

This article discusses the pathophysiology, clinical findings, and imaging features depicted with plain abdominal radiography and abdominal sonography in NEC.

Pathophysiology
The etiology and pathogenesis of NEC remain controversial. It is believed that NEC is secondary to a complex interaction of multiple factors, notably prematurity, that result in mucosal damage, which leads to intestinal ischemia and necrosis (1,2). The mucosal injury may be due to infection, intraluminal contents, immature immunity, release of vasoconstrictors, and inflammatory mediators (3,4). The loss of mucosal integrity allows passage of bacteria and their toxins into the bowel wall and then into the systemic circulation, resulting in a generalized inflammatory response and overwhelming sepsis in the severe forms of NEC (4).

The inflammatory process in NEC leads to increased blood flow in the affected bowel segment. Bacteria penetrate the mucosal defense, and their by-products of metabolism lead to the formation of intramural gas (Fig 1). As NEC progresses, platelet-activating factor produced by inflammatory cells and bacteria propagate the inflammatory cascade, mainly that of cytokines
and complement, leading to extensive transmural involvement (5,6). Eventually, there is compromise of the microvasculature such that ischemic changes to the tissue occur. Finally, the nonperfused bowel wall undergoes necrosis, which may be so severe that sloughing of the bowel wall occurs, resulting in bowel wall thinning and eventually perforation (Fig 1).

**Clinical Findings**

NEC is one of the most common acquired, life-threatening gastrointestinal diseases in the newborn, affecting 1%–5% of neonatal intensive care unit admissions and up to 10% of neonates under 1500 g (7). The incidence of NEC is inversely proportional to the gestational age (8,9). Infants of 28 weeks or less gestational age and those of extremely low birth weight (less than 1000 g) are at a greater risk for NEC (10). However, approximately 10% of neonates with NEC are born at term, and congenital heart disease is the main risk factor in this group (7,9,11,12). Other risk factors include perinatal asphyxia, patent ductus arteriosus, indomethacin therapy, and decreased umbilical flow in utero (12–14).

NEC most commonly manifests within the first or second week of life. However, the time of presentation varies with the gestational age; in very premature neonates, NEC may manifest only in the second or third week of life (6,9,15).

The clinical diagnosis of NEC is often a challenge, as the presentation may vary considerably, is frequently nonspecific, and may be indistinguishable from neonatal sepsis. The symptoms referable to the gastrointestinal tract include feeding intolerance, vomiting, diarrhea, and blood in the stool (15). However, there may also be nonspecific generalized symptoms including lethargy, temperature and blood pressure instability, and apnea. Physical signs include abdominal distention and, in more advanced cases, palpable, distended bowel loops and abdominal wall erythema and edema. Neonates with severe disease may even present in shock (15).

Prompt institution of therapy, which includes bowel rest with a nasogastric tube, antibiotics, and adequate hydration (total parenteral nutrition), is essential to limit clinical progression and the development of complications. Clinical deterioration may result from generalized sepsis or bowel necrosis, which may progress to perforation and the development of peritonitis or intraabdominal abscesses. Bowel perforation occurs in 12%–31% of patients (16). A continuing challenge to the surgeon and radiologist alike is the determination when the most appropriate time for surgical intervention is in those neonates who are not responding to medical therapy or have developed complications. Pneumoperitoneum is the only radiologic sign that has been universally agreed on as an indication for surgical intervention, and this is complicated by the fact that not all neonates with bowel necrosis and perforation have free gas at plain abdominal radiography (15,17).

The overall mortality rate in NEC is between 20% and 40% and is higher in neonates of very low birth weight (15). Mortality climbs to 64% for the very low birth weight infant once perforation has occurred (18,19). Because of the higher mortality rate following perforation, earlier detection of severely ischemic or necrotic loops of bowel before perforation occurs could potentially improve the morbidity and mortality in NEC (17). Imaging may therefore play an important role in this regard (17).

**Imaging Modalities**

The imaging modalities that are used in neonates during the active phase of NEC include plain abdominal radiography and abdominal sonography. Studies that have evaluated the use of contrast examinations of the gastrointestinal tract, computed tomography, and magnetic resonance imaging will not be addressed, as these modalities have not been found to be useful in clinical practice (15,20–23).

**Plain Abdominal Radiography**

Plain abdominal radiography is the current modality of choice for the evaluation of neonates suspected of having NEC. The timing of follow-up plain abdominal radiographs depends on the severity of the NEC and may vary from 6 to 24 hourly. However, plain abdominal radiographs are also required at any time of acute clinical deterioration. In those patients who are resolving clinically, the time interval between plain abdominal radiographs can be progressively prolonged (24).

At the time of diagnosis, plain abdominal radiography must include one image obtained with a vertical beam with the patient supine and a second image obtained with a horizontal beam.
We prefer to obtain a cross-table view with the patient still supine, as this has the advantage that one does not have to move these sick and often labile patients. Both vertical and horizontal beam views are required for follow-up in the first 48 hours following diagnosis, as the vast majority of perforations occur in this time frame. After this, vertical beam views alone may suffice unless there is specific concern for perforation.

The main observations to be made on the plain abdominal radiograph relate primarily to the presence, amount, and distribution of gas, which includes intraluminal gas, intramural gas, portal venous gas, and free intraperitoneal gas (Fig 2). From observations of the intraluminal gas, it may sometimes be possible to make inferences regarding the presence of bowel wall thickening, free fluid, and focal fluid collections.

Abdominal Sonography

The major advantages of abdominal sonography (US) in NEC are that it provides, in real time, direct images of abdominal structures, particularly the bowel, and of fluid in the peritoneal cavity.

Initial studies to evaluate the role of abdominal US in NEC date back to 1984, but no systematic studies—to our knowledge—compared the findings of abdominal US with those of plain abdominal radiography and how these findings may affect management. The emerging role of abdominal US has become particularly evident with the recent publication in 2005 of the first study that assessed bowel viability with color Doppler sonography in neonates with NEC. In that study, Faingold et al established data for bowel wall thickness, echogenicity, peristalsis, and perfusion in the normal neonate and in those with NEC (Fig 3). Their findings showed that abdominal US including color Doppler sonography was extremely helpful for facilitating patient management. Further corroboration of the utility of abdominal US in NEC can also be found in two recent articles by Kim et al, who concluded that evaluation of the bowel wall with gray-scale US was helpful for diagnosis of NEC. It is important to emphasize here that meticulous technique with use of state-of-the-art equipment is essential, and in this regard high-megahertz linear-array transducers are invaluable for depicting the bowel optimally.

Unfortunately, there are no large published studies—to our knowledge—comparing the ability of plain abdominal radiography and abdominal US to depict the abnormalities in neonates with NEC. Abdominal US can certainly depict the gas patterns in the abdomen described in the section on plain abdominal radiography. Although there are limited data available, on the basis of our recent experience we believe that if meticulous attention is paid to technique, abdominal US is in fact more sensitive in detecting intramural gas and portal venous gas and possibly even free gas than plain abdominal radiography. This correlates with what has been shown experimentally and clinically in the two studies by Kim et al. However, what is even more important is that abdominal US offers several advantages over plain abdominal radiography.
other clear advantages over plain abdominal radiography, as it has the ability to depict bowel wall thickness and echogenicity as well as free and focal fluid collections and their character much better than plain abdominal radiography (16,39). Furthermore, real-time abdominal US can depict some features that plain abdominal radiography cannot depict at all. These include the ability to depict peristalsis and the ability of color and power Doppler imaging to show the presence or absence of bowel wall perfusion (17).

Abdominal US does have some relative limitations. Large amounts of bowel gas may make sonographic evaluation of the abdomen difficult, although we have found this to be a problem in only small numbers of neonates with NEC. Faingold et al (17) found that the gray-scale and color Doppler sonograms were not interpretable because of large amounts of bowel gas in only two of 32 neonates with NEC or at risk for NEC. The other limitations relate to the patient’s condition. Abdominal US should not be attempted in any neonate who is labile or unstable, and we have refrained from performing abdominal US if abdominal tenderness is such that holding the transducer on the abdomen causes the patient severe discomfort. However, using a large amount of gel on the abdominal wall may facilitate performance of the study by enabling images to be obtained without the transducer actually touching the abdominal wall.

**Imaging Findings**

**Bowel Gas Pattern**

In normal neonates, gas is most often present through most of the small and large bowel and each gas-filled loop causes an impression on adjacent loops. The loops develop a multifaceted configuration, giving the gas pattern a “mosaic” appearance (Fig 4). The small and large bowel may

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**Figure 3.** Sonographic appearances of normal bowel in a neonate. (a) Gray-scale image shows the typical appearance of collapsed bowel. The echogenic linear markings represent the mucosal interface with the lumen, and the surrounding hypoechoic bands represent the muscularis of the bowel wall. (b) Color Doppler image of normal collapsed bowel shows color dots of flow in the arteries of the bowel wall.

**Figure 4.** Supine radiograph of the abdomen of a normal neonate shows a normal bowel gas pattern. Gas is distributed throughout the small and large bowel, and it is difficult to differentiate the small bowel from the large bowel. Each loop causes impressions on adjacent loops, giving each loop a multifaceted appearance; the overall pattern resembles that of a mosaic. The loops are generally not rounded or elongated.
be impossible to differentiate. However, in many normal neonates the entire bowel may not be filled with gas and, furthermore, dilatation of bowel with retention of the mosaic pattern does not necessarily mean that it is abnormal. Dilatation with loss of the mosaic pattern and the development of rounded or elongated loops is more suggestive that an abnormality is present (Fig 5).

In NEC, bowel dilatation is a nonspecific finding best appreciated on the plain abdominal radiograph and may be the only sign present in many patients with either mild or severe forms of the disease. The dilatation is usually due to an ileus and may be generalized or focal, depending on the extent of bowel involvement. It is the commonest sign, being present in over 90% of patients, with the remaining 10% showing only minor or nonspecific disturbances of bowel gas pattern (Fig 5). Dilatation of bowel is an early sign and may even precede the clinical features of NEC by several hours (40,41). Furthermore, the degree of dilatation usually correlates well with the clinical severity of the disease and the distribution of the dilated loops in serial examinations is related to clinical progression (42) (Fig 6). Resolution of NEC is associated with the dilated bowel gradually returning to a more normal appearance. Persistence of dilatation or a change other than in the normal direction suggests failure of response to medical therapy or deterioration. An ominous sign is the change from generalized dilatation to an asymmetric distribution where dilatation is confined to a more localized area of the abdomen (Fig 6). It is even more worrisome if the asymmetric pattern persists and the dilated loops maintain the same appearance as fixed loops on follow-up plain abdominal radiographs (Fig 6). This suggests the development of full-thickness necrosis and may precede clinical deterioration including signs of peritonitis (42). For these reasons, the degree and pattern of bowel dilatation are the most important signs for early diagnosis and for follow-up (42–45).
It should be emphasized that bowel distention alone is nonspecific and may also be present in premature neonates (especially very low birth weight) who are intolerant of feeding, neonates with an ileus (due to sepsis or electrolyte imbalance), and those receiving continuous nasal positive airway pressure or following resuscitation (15).

Although abdominal US can depict intraluminal bowel gas, it does not display the pattern of gaseous distention as well as plain abdominal radiography. However, in those patients in whom there is a paucity of bowel gas on plain abdominal radiographs, abdominal US can easily be used to determine whether the bowel is normal and is empty and collapsed or whether there is distention due to an increase of intraluminal fluid.

Figure 6. Serial radiographs of a neonate who developed severe NEC on the 14th day of life. (a) Radiograph obtained at presentation shows generalized bowel dilatation with gas, intramural gas mainly in the large bowel, and portal venous gas. The infant’s condition deteriorated clinically, and the parents refused surgery. (b, c) Follow-up images obtained at 8-hour intervals show gradual disappearance of intramural gas and portal venous gas. This finding demonstrates that disappearance of intramural gas and portal venous gas is not a good indicator of clinical progress. The images also show a decrease in the amount of intraluminal gas, which persists as fixed, dilated loops. This appearance is an ominous sign, suggesting the presence of necrotic loops. At no time was there evidence of free intraperitoneal gas.
Intramural gas is also an early sign that may precede clinical signs (40). Although intramural gas may be present in other neonatal conditions, it is most commonly seen in NEC and thus has been considered a virtually pathognomonic sign of NEC (43,44,46). However, intramural gas is not present in all cases of NEC; the incidence varies in reported series from 19% to 98% (43–47).

**Figure 7.** Abdominal radiographs show bowel loops that exhibit the linear pattern of intramural gas. (a) There is a band of radiolucency or black band (black arrow) and a band of soft-tissue opacity or white band (white arrow) along the margin of the involved loop. The black band represents the intramural gas in the serosal layer of the bowel wall, and the white band represents the submucosa and mucosa, which is contrasted on one side by the intramural gas and on the other side by the gas in the lumen. (b) There is extensive intramural gas (arrows) involving almost all of the intestine as well as the stomach in the left upper quadrant. In this patient, the intramural gas is seen as multiple curvilinear black bands, but there are no white bands because the lumen is filled with fluid and there is no gas in the lumen to contrast with the inner aspect of the mucosa.

**Figure 8.** Supine abdominal radiograph of a neonate with clinically very mild or benign NEC. The intraluminal gas present is limited almost entirely to the large bowel, and there is no significant dilatation. There is extensive intramural gas involving the entire large bowel despite the benign clinical course. There are well-developed black and white bands (described in Fig 7) (arrows), which are seen very well in the descending colon and even in the rectum.

**Intramural Gas**

Intramural gas is also an early sign that may precede clinical signs (40). Although intramural gas may be present in other neonatal conditions, it is most commonly seen in NEC and thus has been considered a virtually pathognomonic sign of NEC (43,44,46). However, intramural gas is not present in all cases of NEC; the incidence varies in reported series from 19% to 98% (43–47).
the clinical setting of NEC, the presence of intramural gas confirms the diagnosis of NEC—if not present, the patient may still have NEC and treatment should be commenced if the clinical findings are suggestive of NEC (46).

Intramural gas is more commonly present in the distal small bowel and large bowel and is therefore most commonly seen in the right lower quadrant (Fig 7). However, it may involve any part of the gastrointestinal tract including the stomach (Fig 7) and rectum (Fig 8)—sometimes even in isolation (43,48).

The amount of intramural gas present does not always relate to the clinical severity of NEC in any particular patient (46,48) (Fig 8), and disappearance of intramural gas does not always correlate with clinical improvement (49) (Fig 6). Even large amounts of intramural gas may appear and disappear rapidly—within 12 hours (40).

On plain abdominal radiographs, intramural gas may be diffuse or localized and appears as linear or rounded radiolucencies (Figs 7–10). The linear lucencies often appear curvilinear; they represent intramural gas in the subserosa and appear as black lines on the radiograph, which can occasionally be confused with overlapping bowel loops filled with gas (Figs 7–9). A clue to differentiating intramural gas from overlapping loops are the white lines that often accompany the black lines of intramural gas. The white lines represent the mucosa and submucosa, which are lifted off the serosa and are contrasted by the subserosal intramural gas and the intraluminal gas (Figs 7–9). A search for white lines rather than the black lines may often be more fruitful in helping one confirm the presence of intramural gas. The rounded lucencies represent intramural gas in the submucosa (Fig 10) and when extensive they may have a bubbly appearance, which should not be confused with intraluminal stool.
Figure 11. Sonograms of the bowel wall in NEC show the appearances of varying amounts of intramural gas. (a) The bowel wall is thickened and has a layered appearance. One hyperechoic focus within the wall (close to the cursors) is thought to represent intramural gas. (b) Multiple bowel loops are seen surrounded by some free fluid. There is extensive intramural gas involving all of these loops. The intramural gas has a typical hyperechoic, granular pattern in the bowel wall with posterior reverberation artifacts. With this amount of intramural gas, it is difficult to assess the thickness of the bowel wall.

Figures 12, 13. (12) Sonogram of a bowel loop shows differentiation of intraluminal gas from intramural gas. The intraluminal gas ($L$) is surrounded by a thickened bowel wall. Within the bowel wall are multiple hyperechoic foci (arrows), which represent intramural gas. In this example, the posterior artifact caused by gas is seen only with the larger volume of the intraluminal gas. The bubbles of intramural gas in this patient are too small to cause the posterior artifact, in contrast to the appearance seen in Figure 11b. (13) Sonogram shows a bowel loop with a large amount of intramural gas (arrows) in the more dependent and vertically oriented parts of the loop. This gives the bowel wall a typical granular appearance and causes a posterior artifact.
Abdominal US depicts intramural gas as hyperechoic foci in the bowel wall (Figs 11–14) (17,26,27,37,38,50). The amount of intramural gas may vary considerably from single or scattered hyperechoic foci in the wall to complete circumferential involvement of the wall of one or many bowel loops (Fig 11). Large amounts of intramural gas may give the wall a speckled or granular appearance, which can be confused with dense calcification. However, the latter usually has a much sharper posterior acoustic shadow than intramural gas (Fig 15). Small amounts of intramural gas in the nondependent portions of a bowel loop have to be differentiated from small amounts of intraluminal gas floating between the intraluminal fluid and the nondependent portion of the bowel wall (Fig 14). Small amounts of intramural gas are less likely to be confused with intraluminal gas when the dependent portion of the bowel wall is involved (Figs 11, 13). In contrast to intraluminal gas, intramural gas will not change position because of peristalsis, respiratory movement, changes of the patient’s position, or abdominal compression with the transducer (27,37,50,51).

**Portal Venous Gas**

The commonest cause of portal venous gas in neonates is the passage of small amounts of gas through an umbilical venous catheter in the absence of NEC (52) (Fig 4). In NEC, portal venous gas is an extension of intramural gas that enters the veins of the bowel wall and passes into the portal venous system. The amount of portal venous gas is not always related to the amount of...
intramural gas present, and the portal venous gas may be more obvious than the intramural gas (48). Portal venous gas has been reported on plain abdominal radiographs in up to 30% of neonates with NEC (53,54), and these are usually, but not always, the more severely affected cases. Portal venous gas is not always associated with a fatal outcome.

Portal venous gas is not as early a sign as intramural gas. However, like intramural gas, portal venous gas may appear and disappear rapidly, and it is possible that in many instances it is missed (45,55,56). Its disappearance is not always associated with clinical improvement (Fig 6).

On a supine plain abdominal radiograph, portal venous gas appears as branching, linear, radiolucent vessels that may extend from the region of the main portal vein toward the periphery of both hepatic lobes, and the extent depends on the amount of portal venous gas present (Fig 16). Occasionally, it is more easily appreciated on the lateral cross-table view of the abdomen than on the supine view (Fig 16). Portal venous gas must be differentiated from gas in the biliary tree, which is uncommon in the neonatal period and is more centrally located in the larger ducts, in contrast to portal venous gas, which may extend more peripherally (54).

At gray-scale abdominal US, portal venous gas may be seen in the main portal vein and its major branches as intraluminal echogenic foci moving
with the blood flow (Fig 16). Doppler interrogation of these vessels will reveal a typical artifact at spectral analysis caused by the gas in the blood, which can be appreciated audibly as a crackle and visually on the spectral tracing as sharp bidirectional spikes of Doppler shift superimposed on the portal venous waveforms. In the smaller intraparenchymal portal branches, portal venous gas is seen as hyperechoic foci that, when sufficient enough, form a linear, branching pattern (Fig 16). This pattern may be seen diffusely throughout the liver or may have a more focal distribution in either lobe.

Free Intraperitoneal Gas
Free gas in the peritoneal cavity results from bowel perforation, which most commonly occurs in the distal ileum and proximal colon. It is the only universally accepted radiologic indication for surgical intervention (15).

Plain abdominal radiography has been the standard method for detection of the presence of free gas (Figs 2, 17). The view obtained with the horizontal beam is particularly useful for detecting small amounts of gas (57). On the cross-table lateral view, free gas may appear as triangular lucencies between loops of bowel anteriorly just beneath the abdominal wall (Figs 2, 17) or as small bubbles or linear gas collections anterior to the liver (Fig 17). On the left lateral decubitus view, small amounts of gas may be seen between the right lobe of the liver and the right lateral abdominal wall. However, on the supine view, large amounts of gas may give rise to the “football” sign, where the gas outlines the whole of the peritoneal cavity, the undersurface of the diaphragm, and the falciform ligament (the lacing of the football). Smaller amounts of free gas may give rise to lucency below the diaphragm without giving rise to the full-blown football sign. Even on the supine view, smaller amounts of free gas may be detected when both sides of the bowel wall are outlined (Rigler sign).

Although abdominal US has not been the standard method used to detect free gas, this modality may indeed depict small or large volumes of free gas (17). Small volumes may be detected as hyperechoic foci with dirty shadowing either between the anterior surface of the liver and the abdominal wall, between bowel loops, or floating on
free peritoneal fluid just deep to the abdominal wall (17) (Fig 18). It may sometimes be possible to visualize small hyperechoic foci of free gas leaking out of necrotic bowel loops and rising to the nondependent aspect of free fluid just deep to the abdominal wall (Fig 18). Larger amounts of free gas may be difficult to differentiate from intraluminal gas. However, it is indeed possible to differentiate the two, as the larger amounts of free gas appear as sheets of echogenicity just deep to the abdominal wall and do not conform to the shape of bowel loops as intraluminal gas does (Fig 18).

Also, the free gas is not subject to changes in shape due to peristalsis as intraluminal gas is.

Abdominal Fluid

The first major advantage of abdominal US over plain abdominal radiography is its ability to depict abdominal fluid, whether this is intraluminal or extraluminal and whether it is free in the peritoneal cavity or a more localized fluid collection. It must be stressed that a small amount of free intraperitoneal fluid is a normal finding in normal neonates (17). Furthermore, larger amounts of intraperitoneal fluid may also be seen with other conditions not related to NEC, including cardiac failure and anasarca.

Figure 18. Sonograms show the spectrum of appearances of free intraperitoneal gas. (a) A large amount of free intraperitoneal gas appears as a long, linear area of echogenicity (arrow) just deep to the abdominal wall and causes a posterior reverberation artifact. This finding may be difficult to differentiate from the appearance caused by several bowel loops filled with gas. (b) Smaller amounts of free intraperitoneal gas are depicted between the anterior abdominal wall and the left lobe of the liver as echogenic foci (arrow). These foci may vary in size, and the amount of gas present will determine whether there is a posterior artifact. The space between the liver and abdominal wall is ideal to evaluate for free gas, as bowel is seldom present in this location. (c) Bowel loops are seen with free fluid between them and the abdominal wall. During real-time imaging, echogenic foci (arrow) could be seen bubbling out of one of the loops; the echoes rose in the free fluid until they were just deep to the abdominal wall. The echogenic foci represent free gas bubbling out through an area of perforation.
Accumulation of free intraperitoneal fluid can be seen in neonates with more severe NEC with or without perforation (37). The presence of low-level echoes or septations within the fluid is more suggestive of perforation (Fig 19), as they suggest the presence of pus or intestinal contents (16,39). However, these findings are nonspecific and have to be correlated with other findings at abdominal US.

It has to be remembered that perforation may be associated with the accumulation of intraperitoneal fluid in the absence of free gas at plain abdominal radiography (15), and in this regard abdominal US plays a major role, as it is much more accurate in depicting small or even larger amounts of free fluid than plain abdominal radiography (16,19). Furthermore, abdominal US can depict localized fluid collections and abscess formation, which are not uncommonly seen in severe NEC. Abscesses often contain septations and echogenic material (Fig 20).

**Bowel Wall**

*Thickenss, Echogenicity, and Peristalsis.*—It is difficult to determine bowel wall thickness from the plain abdominal radiography findings in a neonate. One attempts to do this by observing the bowel gas pattern and then indirectly attempting to infer the thickness of the wall by assessing the distance between the intraluminal gas in two adjacent loops of bowel. The observation is subjective and there are no standard measurements available for comparison. Furthermore, there are several factors that complicate the observation because the distance between the gas in adjacent loops is not simply related to bowel wall thickness alone. It also depends on the amounts of intraluminal and interloop fluid present, as both can push the visible intraluminal gas further apart, simulating bowel wall thickening. Bowel wall thinning, a more severe event in NEC, is even more difficult to define on plain abdominal radiographs if not impossible.
The second major advantage of abdominal US in NEC is that it is possible with this modality to visualize the bowel wall directly and to assess bowel wall thickness, echogenicity, and peristalsis. In the 30 normal neonates studied by Faingold et al (17), bowel wall thickness ranged from 1.1 to 2.6 mm (mean, 1.72 mm; SEM, 0.05). The normal neonatal bowel echogenicity (so-called gut signature) showed a particularly prominent hypoechoic rim or halo, which was thought to represent the muscularis propria (Fig 3). There was no significant interference from the presence of bowel gas.

In 22 neonates with proven NEC and eight at risk for NEC studied by Faingold et al (17), thickening of the bowel wall was seen in all 30 (Figs 21, 22). Thinning of the bowel wall was also noted in eight of these, all of whom had severe NEC (Fig 23). Peristaltic activity was lost in all of the more severely affected neonates and in approximately 30% of those less severely affected.
With both bowel wall thickening and thinning, the normal echogenicity of the bowel wall is lost and it may be difficult to resolve the bowel wall from echogenic intraluminal contents in more severely affected loops (Fig 21). Bowel wall thickening is accompanied by an increase in echogenicity of the full wall thickness, often associated with a hyperechoic rim along the damaged mucosa (Fig 21). Thickening and increased echogenicity of the valvulae conniventes of the small bowel may give rise to a gray-scale “zebra” pattern (Fig 22). However, bowel wall thickening associated with increased echogenicity is a non-specific sign, as we have also seen this in neonates with other causes of diffuse edema in the absence of inflammation or ischemia.

Thinning of the bowel wall was first documented by Faingold et al (17), who defined thinning as less than 1 mm in thickness, although measurements at this level may be difficult to achieve accurately (Fig 23). The presence of larger amounts of intramural gas may make recognition of the bowel wall thinning difficult. Abnormal thinning in NEC must be differentiated from apparent thinning due to stretching of the wall of fluid-distended loops in patients with or without NEC. In the latter instance, the wall retains its normal echogenicity and peristalsis may be preserved.

**Figure 23.** Thinning of the bowel wall in NEC. Sonogram shows a bowel loop filled with content of mixed echogenicity and surrounded by clear free fluid. The bowel wall is of various thicknesses but is particularly focally thinned at one site (arrow).

**Figure 24.** Color Doppler sonograms show hyperemic bowel loops in NEC. Each loop appears thickened and has lost the normal bowel wall echogenicity. (a) There is a “Y” pattern of flow outlining the mesenteric and subserosal vessels of the bowel loop (arrow). (b) There is a “ring” pattern of flow with flow seen around the entire circumference of the bowel loop (arrow). The mesenteric vessels are also prominent, and there is flow around most of the adjacent loop. These hyperemic patterns of flow are not seen in normal neonates, and in neonates with NEC these patterns indicate viable loops.

**Bowel Wall Perfusion.**—The third major advantage of abdominal US is the ability of this modality to directly assess arterial perfusion of the bowel wall, as this is not possible with plain abdominal radiography. On the basis of the perfusion, one may infer the viability of individual loops. In the 30 normal neonates studied by Faingold et al (17), bowel wall perfusion was detected with color Doppler sonography in all. Artifacts due to large amounts of bowel gas or patient motion made detection of color Doppler signals impossible in parts of the abdomen in a small minority of neonates.

In the group of 32 neonates with proven NEC or at risk for NEC reported by Faingold et al (17), gray-scale and color Doppler sonograms were not interpretable due to large amounts of bowel gas in only two patients. In the 22 neonates with NEC, three categories of flow in the bowel wall were recognized at color Doppler sonography: normal, increased, and absent.

Flow was considered increased if the number of signals identified (using the standardized technique) was above that described in the normal control group (17). In most instances, this hyperemic flow is so obvious to even the untrained observer that no measurements of dots or lines are necessary (Figs 22, 24). Therefore, the documentation of hyperemia can indeed be made...
subjectively. Moreover, additional changes of increased flow described by Faingold et al (17) can be identified when one sees certain specific flow patterns that are not seen in normal neonates or in those neonates with bowel wall thickening for reasons other than NEC. These flow patterns include a “zebra” pattern when one identifies multiple, parallel color Doppler lines due to flow in hyperemic valvulae (Fig 22); a “Y” pattern due to color Doppler flow in distal mesenteric and subserosal vessels (Fig 24); and a “ring” pattern due to circumferential flow around the entire bowel wall (Figs 24, 25). It is suggested that the hyperemia is the result of vasodilatation of mural and mesenteric vessels secondary to intestinal inflammation (5,17). Loops exhibiting this pattern are thought to correspond to inflamed viable bowel in NEC (17). Furthermore, it is apparent that hyperemic perfusion of the bowel wall in NEC is characterized by loss of the normal arterial pulsatility, probably due to the vasodilatation and resultant reduced resistance.

Flow was considered absent when no color Doppler signals were identified in the bowel wall (Fig 25) and correlated with transmural bowel necrosis in histologic specimens from laparotomy and autopsy or with pneumoperitoneum at plain abdominal radiography (17). Patient outcome correlated with the number of bowel loops exhibiting absent flow. Bowel loops with absent flow were not found in normal neonates or in those only at risk for NEC. Color Doppler sonography was found to be more accurate than clinical examination and plain abdominal radiography in the prediction of necrosis in neonates with NEC (17).

At abdominal US, the findings of bowel wall thickening or thinning, lack of peristalsis, and abnormalities of perfusion are more often found in the lower abdomen, particularly in the right lower quadrant. At follow-up abdominal US in more severely affected patients, these bowel appearances may not change and may appear fixed.

The changes described in bowel wall thickness, echogenicity, and perfusion are summarized in Figure 26, which illustrates our concept of the sequence of the sonographic changes that take place in NEC.

**Role of the Radiologist**

Because the early and late clinical findings are nonspecific, the radiologist plays an important role at the time of diagnosis, during evaluation of progress in the acute phase, and for detection of complications (42). The radiologic signs may precede the clinical signs, and the radiologist is thus in a position to not only be the first to suspect or diagnose the condition but may, even more importantly, be the first to predict or detect the presence of complications that require surgery (42).
At presentation, the presence of intramural gas in the clinical setting of NEC virtually clinches the diagnosis. In the absence of intramural gas, diagnosis may be much more difficult, especially if the clinical findings are mild and nonspecific. In such patients, interpretation of the plain abdominal radiograph may be a frustrating experience (37) if the only finding is mild gaseous distention or if there is a suggestion of bowel wall thickening. It is in these patients with mild symptoms and nonspecific findings at plain abdominal radiography that abdominal US may be extremely useful, as it may be able to depict intramural gas not visible on plain abdominal radiographs (17,37) as well as depict changes in bowel wall thickness, echogenicity, peristalsis, and perfusion that may enable one to confirm or exclude the diagnosis of NEC.

Once the diagnosis of NEC has been established, interval plain abdominal radiographs are essential for appropriate follow-up. The disappearance of intramural gas and portal venous gas is not always associated with clinical improvement, and these are thus poor indicators of progress. On the other hand, the change of the distribution of dilated bowel loops is of utmost importance in evaluating progress (Fig 6).

When to perform abdominal US during follow-up and how often has not been established. In those neonates who respond promptly to medical therapy, abdominal US probably has no role. However, it may play a significant role in two groups of patients. The first group includes those neonates in whom the evolution of changes at plain abdominal radiography is not in keeping with the clinical course, and the second group includes those who are deteriorating clinically but have no evidence of pneumoperitoneum at plain abdominal radiography. In the latter group, it is always a challenge to decide whether to operate in the absence of pneumoperitoneum. We have found that in both of these groups, abdominal US provides valuable information regarding the bowel wall and peritoneal cavity that may influence management (17).

Kim et al (37) have suggested that monitoring with abdominal US may also be helpful in determining the most appropriate time to reintroduce and advance feeding, and it may also be used to differentiate recurrent NEC from other causes of bowel distention.
Conclusions
Plain abdominal radiography remains the current modality of choice for evaluation and follow-up of neonates with NEC, but this modality is not without its limitations. The major advantages of abdominal US over plain abdominal radiography are that abdominal US can depict intraabdominal fluid, bowel wall thickness, and bowel wall perfusion. However, further large prospective studies are required to better define the role that abdominal US should play and to establish whether abdominal US should be used routinely in all neonates with NEC or in selected patients at the time of diagnosis or follow-up.

References
Necrotizing Enterocolitis: Review of State-of-the-Art Imaging Findings with Pathologic Correlation

Monica Epelman, MD et al

Plain abdominal radiography is the current modality of choice for the evaluation of neonates suspected of having NEC.

Although abdominal US has not been the standard method used to detect free gas, this modality may indeed depict small or large volumes of free gas (17).

The first major advantage of abdominal US over plain abdominal radiography is its ability to depict abdominal fluid, whether this is intraluminal or extraluminal and whether it is free in the peritoneal cavity or a more localized fluid collection.

The second major advantage of abdominal US in NEC is that it is possible with this modality to visualize the bowel wall directly and to assess bowel wall thickness, echogenicity, and peristalsis.

The third major advantage of abdominal US is the ability of this modality to directly assess arterial perfusion of the bowel wall, as this is not possible with plain abdominal radiography.