Received:
16 August 2017

Revised:
07 February 2018

Accepted:
23 February 2018

<https://doi.org/10.1259/bjr.20170600>

Cite this article as:

Koo CW, Johnson TF, Gierada DS, White DB, Blackmon S, Matsumoto JM, et al. The breadth of the diaphragm: updates in embryogenesis and role of imaging. *Br J Radiol* 2018; **91**: 20170600.

REVIEW ARTICLE

The breadth of the diaphragm: updates in embryogenesis and role of imaging

¹CHI WAN KOO, MD, ¹TUCKER F JOHNSON, MD, ²DAVID S GIERADA, MD, ¹DARIN B WHITE, MD, ³SHANDA BLACKMON, MD, MPH, ¹JANE M MATSUMOTO, MD, ^{1,4}JOOAE CHOE, MD, ³MARK S ALLEN, MD, ¹DAVID L LEVIN, MD, PhD and ¹RONALD S KUZO, MD

¹Department of Radiology, Mayo Clinic, Rochester, MN, USA

²Department of Radiology, Washington University School of Medicine, Mallinckrodt Institute of Radiology, St. Louis, MO, USA

³Department of Thoracic Surgery, Mayo Clinic, Rochester, MN, USA

⁴Department of Radiology, Asan Medical Center, Seoul, South Korea

Address correspondence to: Dr Chi Wan Koo

E-mail: koo.chiwan@mayo.edu

ABSTRACT

The diaphragm is an unique skeletal muscle separating the thoracic and abdominal cavities with a primary function of enabling respiration. When abnormal, whether by congenital or acquired means, the consequences for patients can be severe. Abnormalities that affect the diaphragm are often first detected on chest radiographs as an alteration in position or shape. Cross-sectional imaging studies, primarily CT and occasionally MRI, can depict structural defects, intrinsic and adjacent pathology in greater detail. Fluoroscopy is the primary radiologic means of evaluating diaphragmatic motion, though MRI and ultrasound also are capable of this function. This review provides an update on diaphragm embryogenesis and discusses current imaging of various abnormalities, including the emerging role of three-dimensional printing in planning surgical repair of diaphragmatic derangements.

DEVELOPMENT OF THE DIAPHRAGM

Development of the diaphragm occurs during weeks 4–12 of embryonic life (Figure 1 and Supplementary video 1).^{1,2} The septum transversum, a thin mesodermal plate that provides scaffolding and forms the floor of the pericardial cavity, separates the thorax and abdomen. The pleuroperitoneal folds FORM next and are positioned laterally in the embryo. Subsequently, the post-hepatic mesenchymal plate (PHMP) forms. This structure grows in a laterodorsal direction to close the pleuroperitoneal canals and seals the thorax from the abdomen. Ingrowth of progenitor cells from somites form the muscular portions of the diaphragm. Recent research found that abnormal development of the post-hepatic mesenchymal plate due to genetic derangements is central in the formation of congenital diaphragmatic hernias.^{3–5}

CONGENITAL ABNORMALITIES OF THE DIAPHRAGM

Congenital hernias

Bochdalek hernia

Bochdalek hernias result from incomplete closure of the embryonic pleuroperitoneal membrane. Despite the name, they typically occur through posterolateral defects in the

diaphragm that are separate from the foramen of Bochdalek.⁶ The defects also occur medially and are of variable size. These hernias are seen more commonly on the left, an observation that has been attributed to earlier closure of the right pleuroperitoneal membrane⁷ and protection by the liver.⁸

In the neonatal period, a large congenital diaphragmatic hernia is a surgical emergency.⁹ The initial chest radiograph usually reveals a space-occupying lesion of the hemithorax and contralateral shift of the mediastinum, caused by herniation of the abdominal contents into the chest. Morbidity and mortality are related to the degree of underlying pulmonary hypoplasia. Prenatal diagnosis is possible with the use of fetal ultrasonography or MRI.¹⁰

In adults, a Bochdalek hernia is usually asymptomatic and discovered incidentally by chest radiography or CT. Such incidental hernias may be more frequent on the right side.¹¹ The concomitant diaphragmatic defect is easily seen on CT or MRI. Other radiologic modalities also may demonstrate the hernia contents: barium studies may reveal herniated bowel loops; intravenous urography may reveal a herniated kidney; and radionuclide imaging may demonstrate hepatic or splenic herniation. If bowel or organs are involved, there

Figure 1. Final image of normal diaphragm development illustration (Please see supplemental video for full illustration).

is a risk of bowel obstruction and strangulation (Figure 2).¹² Small focal diaphragmatic defects, with or without herniated fat or viscera, may be seen in more than 5% of adults on CT.^{13,14} Their increasing incidence with age and emphysema strongly suggests that most such abnormalities are acquired and are not true congenital Bochdalek hernias.¹⁴

Morgagni hernia

Foramen of Morgagni hernias are related to maldevelopment of the embryologic septum transversum with failure of fusion of the sternal and costal fibrotendinous elements of the diaphragm.^{7,15} In contrast to the true Bochdalek hernia, a hernia sac of peritoneum and pleura surrounds the contents of a Morgagni hernia.¹⁶ Morgagni hernias are often associated with obesity and most often right-sided, probably because left-sided defects are covered by the heart and pericardium.

Morgagni hernias usually come to clinical attention as asymptomatic right cardiophrenic angle masses on chest radiographs. The finding of omental vessels coursing across the parasternal diaphragmatic defect facilitates CT diagnosis (Figure 3). The actual defect may be difficult to identify because of its typically small size. CT readily permits distinction from other causes of cardiophrenic angle masses by revealing abdominal viscera, omental fat and vessels peripheral to the diaphragm in the lower anterior chest. As with Bochdalek hernias, multiplanar MRI is occasionally useful.

Figure 2. Coronal CT of a congenital Bochdalek hernia (a), initially contains non-obstructed large bowel with subsequent development of bowel obstruction (b).

Figure 3. Axial and coronal CT images (a, b) of a large Morgagni hernia demonstrate mesenteric vessels and mesenteric fat extending from the parasternal portion of the diaphragm to the herniated bowel loops filling the right lower hemithorax. The white arrows indicate the hemidiaphragm and the red arrow denotes the vessels.

Accessory diaphragm

Accessory, or duplicated, diaphragm is a rare congenital anomaly in which a thin, fibromuscular membrane is attached to the diaphragm anteriorly and courses posterocranially to attach to the posterior rib cage.^{17–22} CT or MRI may be helpful in suggesting the diagnosis and identifying associated congenital anomalies, particularly pulmonary hypoplasia.²¹

ACQUIRED ABNORMALITIES AFFECTING THE DIAPHRAGM

Acquired hernias

Hiatal hernia

Hiatal hernia is the most frequently encountered diaphragmatic hernia in adults. Acquired enlargement of the esophageal hiatus and laxity of the phrenoesophageal ligament are etiologic factors, often associated with conditions resulting in increased intra-abdominal pressure, such as obesity and pregnancy.^{7,16} Sliding hiatal hernias (Type I) are more common than the paraesophageal (Type II) variety, in which the stomach herniates up alongside the lower esophagus while the gastroesophageal junction remains underneath the diaphragm.

On chest radiography, hiatal hernias are depicted as lower posterior mediastinal, retrocardiac soft tissue masses, often containing an air-fluid level. The diagnosis can be confirmed by a barium esophagogram, although this is rarely necessary. Very large hernias can become incarcerated or undergo volvulus (Figure 4).²³ Multidetector CT or multiplanar MRI can be useful to define the contents of large hiatal hernias when operative repair is planned.

In fact, cross-sectional imaging serves as the springboard from which three-dimensional (3D) models are created.²⁴ 3D models can assist in critical surgical planning for complex hernias, enabling individualized medicine since each patient's abnormality is mapped out precisely prior to surgery (Figure 5). Moreover, 3D models are essential in designing and testing innovative reconstruction surgeries. Consulting with the surgical team, the important anatomy to be printed is selected on a patient's MRI and/or CT. The 3D modeling team segments the requisite anatomy and creates a computerized 3D image of the model. The 3D modeling program typically allows fusion of different

Figure 4. Upper gastrointestinal series demonstrates a large paraesophageal hernia, manifesting as an intrathoracic stomach. The gastric fundus (F) is rotated posteroinferiorly, consistent with organoaxial rotation.

structures from an MRI, CT or both to achieve the best anatomic depiction. The optimal material to construct the 3D model is selected. The model is printed by a multimaterial 3D printer, which deposits layers of photopolymers that are subsequently hardened by ultraviolet light. After washing and drying, the model is ready for review by multidisciplinary teams for surgical planning and for educating trainees and patients.

Traumatic hernia

Traumatic diaphragmatic hernia usually results from either blunt or penetrating injury. Diaphragm rupture has been recognized in less than 6% of blunt trauma survivors.^{25–28} It affects the left hemidiaphragm more frequently, possibly because of protection of the right hemidiaphragm by the liver or inherently greater weakness of the left hemidiaphragm.²⁹ Infrequently, bilateral diaphragmatic rupture occurs.^{25–28,30–32} Blunt traumatic tears can involve

Figure 5. Presurgical planning for a patient with a large paraesophageal hernia utilizing 3D modeling starts with segmentation of the necessary structures (a), followed by construction of a 3D computer model (b). Final product after supporting material has been removed (c). 3D, three-dimensional.

Figure 6. Frontal chest radiograph of a male after a motor vehicle accident shows the nasogastric tube coiled in the herniated intrathoracic stomach.

any portion of the diaphragm,³³ although they usually involve the posterior central aspect of a hemidiaphragm and extend radially, or they can result in disruption of the posterolateral attachments.^{25,34} Blunt traumatic defects are usually large, often more than 10 cm in length.^{15,27,31,35} Penetrating trauma due to stab wounds most often affects the left hemidiaphragm because most people are right-handed, whereas gunshot wounds affect both sides equally.³¹ Penetrating wounds are usually less than 2 cm in length.³⁵ Though exceedingly rare, diaphragm rupture and hernia may occur spontaneously from sudden increases in abdominal pressure, such as with vomiting, parturition, coughing, and vigorous physical exertion,³⁶ or after thoracoabdominal surgery.³⁷

No reliable clinical signs or symptoms indicating diaphragmatic rupture have been identified.²⁶ Abdominal injuries managed conservatively can be monitored by imaging, precluding identification of diaphragmatic tears that would have been detected during exploratory laparotomy. Early diagnosis, therefore requires a high degree of suspicion, which is important because the pleuroperitoneal pressure gradient can cause defects to enlarge over time,^{31,38} with eventual bowel obstruction, incarceration, and strangulation.^{33,39–43}

Detection sensitivities for diaphragmatic rupture on chest radiographs is typically less than 50% (range from 20 to 71%).^{25–28,31,32,39} The disparate sensitivities from prior studies is likely multifactorial, including simultaneous lung pathology that mask or mimic diaphragmatic rupture and delayed presentation when certain studies may have accounted for initial radiographs only. Herniation of hollow viscera into the chest and intrathoracic stomach with a nasogastric tube (Figure 6) are the most specific radiographic signs. Diaphragm rupture should be suspected whenever radiographs reveal apparent elevation of

Figure 7. Initial (a) and post-admission (b) radiographs obtained in a male, who fell 30 feet show new apparent elevation of the left hemidiaphragm suspicious for interval development of a diaphragmatic hernia. Multiplanar reformatted CT (c-e) images reveal herniation of the stomach through a traumatic defect in the medial left hemidiaphragm (*white arrows* at margins of defect). Note constriction of stomach by the defect (*collar sign*) and contact of herniated portion of stomach with posterior chest wall (*black arrows* denote the dependent viscera sign).

a hemidiaphragm, although this can be caused by atelectasis, eventration, diaphragm paralysis, or subpulmonic pleural effusion. Right-sided rupture is more difficult to detect radiographically; one study suggests that a 4–5 cm or greater elevation of the right hemidiaphragm relative to the left should be considered

Figure 8. Frontal chest radiograph in a female after a car accident shows normal diaphragmatic position. CT image obtained on admission shows thickening of the right crus (arrows) that can be interpreted as an indirect sign of traumatic rupture. Imaging obtained 1 week later reveals herniation of the liver with narrowing at the level of the diaphragm defect (*collar sign*).

highly suspicious for right-sided rupture in the setting of blunt trauma.³⁷

Evidence of rupture may not be present on the initial radiograph but may develop on subsequent studies, thus serial imaging is helpful.^{26,27,32,40} Other radiographic findings of diaphragm injury include basal lung opacity and abnormal hemidiaphragm contour. Rarely, herniated omental fat can simulate pleural fluid on chest radiographs.⁴⁴ Radiographic findings are absent or nonspecific in most penetrating injuries, and early diagnosis typically requires direct inspection.⁴⁵

The sensitivity and specificity of CT in diagnosing traumatic diaphragmatic hernias is approximately, 80% (range from 61 to 100%) and above 90% (range from 77 to 100%) respectively, better for left- than for right-sided ruptures.^{46–49} The disparate results seem to stem from the fact that most studies lack adequate power as surgically proven diaphragmatic rupture is rare. Intrapericardial herniation occurs rarely but may be demonstrated by CT.^{50,51} The presence of any one of these signs indicate a substantial chance of diaphragm rupture.^{34–49,52–57}

- (1) Contact of the upper third of the liver on the right or the stomach or bowel on the left with the posterior ribs (*dependent viscera sign*) (Figure 7)
- (2) Abdominal structures external to the diaphragm (Figure 7)
- (3) Focal constriction of the hernia contents (*collar or hourglass sign*) (Figure 7)
- (4) A focal bulge along the diaphragm (or *cottage loaf sign*, a variation of the collar sign) (Figure 8)
- (5) Linear lucency across the liver along the torn edge of the hemidiaphragm (*band sign*)
- (6) Abrupt discontinuity of the diaphragm (Figure 8), with or without visceral herniation (cautious with this sign as small defects are frequently seen in asymptomatic persons)

scanned for indications other than trauma)

- (7) Inability to identify the diaphragm (absent diaphragm sign) in an area where it does not contact another organ and should normally be seen
- (8) Acute arterial extravasation of contrast at the level of the diaphragm
- (9) Diffuse or focal thickening of the diaphragm [Figure 9](#)
- (10) Injured diaphragm curled inward from its normal course parallel to the body wall (dangling diaphragm sign)

Isolated small defects from penetrating trauma, in the absence of other injuries, may be difficult to detect in the absence of herniation. Such small defects may result in delayed herniation if they are not detected and repaired ([Figure 7](#)), therefore, laparoscopic or thoracoscopic evaluation may be indicated with certain injuries.^{58,59} Cross sectional imaging such as MRI or CT with multiplanar reformatting ([Figure 7](#)) can be helpful.⁵² Use of MRI is generally limited to nonemergent settings where delayed diagnosis is sought.^{28,60–63}

Other imaging techniques such as ultrasound can be of value in assessing the right hemidiaphragm by depicting the free edge of the diaphragm as a flap within pleural fluid²⁹ or by demonstrating liver herniated into the chest.⁶⁴ Scintigraphy can demonstrate traumatic herniation of the liver or spleen. Fluoroscopic upper or lower gastrointestinal studies may demonstrate herniated segments, particularly in delayed presentations.

Abnormalities of diaphragm position

Apparent or actual hemidiaphragm elevation has numerous causes ([Table 1](#)). Conversely, causes of hemidiaphragm depression ([Table 2](#)) are more limited.

Paralysis of the diaphragm

Diaphragm paralysis may result from an abnormality at any point along its neuromuscular axis, may be unilateral or bilateral, and has numerous potential causes.^{7,65–68} Invasion by a malignant neoplasm and phrenic nerve trauma related to surgery (stretch, crush, or transection) ([Figure 10](#)) are common causes, although many cases are idiopathic. Central nervous system conditions also have been associated with bilateral hemidiaphragm paralysis. Hypothermic injury of the phrenic nerve related to the use of cold topical cardioplegia during coronary artery bypass surgery can lead to hemidiaphragm

Table 1. Causes of hemidiaphragm elevation

Unilateral
Volume loss (atelectasis, lobar collapse, partial lung resection, radiation fibrosis, congenital pulmonary hypoplasia, pleural encasement by tumor)
Eventration
Abdominal disease (dilated stomach or colon, hepatomegaly, splenomegaly, subphrenic abscess)
Phrenic nerve paralysis
Splinting (rib fracture, pneumonia, infarction, abscess, cholecystitis, peritonitis)
Mimics (subpulmonic pleural effusion, large pleural mass, diaphragmatic hernia)
Single-lung transplantation for pulmonary fibrosis
Phrenoplasty
Bilateral
Volume loss (suboptimal inspiration, supine positioning, atelectasis, lung resection, pulmonary fibrosis)
Abdominal mass effect (obesity, pregnancy, marked bowel dilation, ascites, hepatosplenomegaly, large abdominal tumor)
Eventration
Subpulmonic pleural effusion (mimics hemidiaphragm elevation)
Neuromuscular disease (quadriplegia, multiple sclerosis, amyotrophic lateral sclerosis, Guillain-Barré syndrome, myasthenia gravis, Eaton-Lambert syndrome, muscular dystrophy, steroid or alcohol myopathy, rhabdomyolysis)
Connective tissue disease (fibrosis in rheumatoid arthritis, scleroderma, and ankylosing spondylitis; weakness in systemic lupus erythematosus, polymyositis)
Endocrine and metabolic disorders (hypothyroidism, hyperthyroidism, Cushing's disease, hypokalemia, hypophosphatemia, hypomagnesemia, metabolic alkalosis)
Phrenic nerve paralysis

paralysis, usually on the left, which may persist for longer than 1 year.⁶⁷ Diaphragm weakness without paralysis can be found in numerous conditions, including myopathies, connective

Figure 9. Posteroanterior (a) chest radiographs of a patient who had sustained a left upper quadrant stab wound 2 years earlier shows apparent focal elevation of the anterolateral left hemidiaphragm (hump sign). CT image (b) shows the stomach (St) passing through defect in left hemidiaphragm (arrows at margins of defect). Note edema within fat adjacent to the anterior margin of the defect. A strangulated hernia was found at surgery.

Table 2. Causes of hemidiaphragm depression

Unilateral
Large pneumothorax
Asymmetrical bullous emphysema
Large pleural effusion
Foreign body aspiration
Congenital lobar emphysema
Single-lung transplantation for emphysema
Bilateral
Chronic obstructive pulmonary disease (emphysema, asthma)
Deep inspiration (young, thin person)
Bilateral large pneumothorax
Bilateral large pleural effusion
Mechanical ventilation at high pressures
Cystic fibrosis
Pulmonary histiocytosis X
Lymphangioleiomyomatosis

tissue diseases, and various endocrine and metabolic disorders (Table 1).

Fluoroscopy is the most efficient method of assessing diaphragm motion. Other methods include ultrasound, comparison of radiographs obtained in full inspiration and expiration and MRI. With improved technology, MRI “sniff testing” is possible (Figure 11, Supplementary video 2). Unlike fluoroscopy, MRI offers the

Figure 10. Radiograph obtained 1 month after left carotid endarterectomy shows left hemidiaphragm elevation that persisted and was suspicious for cervical phrenic nerve injury. Fluoroscopy confirmed left phrenic nerve paralysis.

Figure 11. Image from a MRI sniff test (Please see , for full illustration) demonstrating MRI's capability for visualizing extra-diaphragmatic pathologies (note the left pleural effusion) in addition to assessing diaphragmatic function, which may explain or are associated with patient's symptoms.

advantage of superior depiction of extradiaphragmatic pathologies while imparting no radiation on the patient. Similarly, sonography has recently become more popular for anatomic and functional diaphragmatic evaluation due to its radiation-free and mobile nature where exams can be performed by bedside. Ultrasound's portability is particularly useful in assessing patients with respiratory failure following cardiothoracic surgery, where early intervention can facilitate successful weaning from mechanical ventilation and prevent ventilator-associated as well as lengthy hospitalization comorbidities. Ultrasound has been shown to be similar in accuracy to most other imaging modalities in diaphragm assessment.⁶⁹ Unlike fluoroscopy which assesses the anterior central tendon, sonography focuses on the posterior and lateral diaphragm which are the muscular components innervated by the phrenic nerve and move more with respiration. Sonographic techniques have been described previously with B mode measuring diaphragmatic thickening while M mode assessing diaphragmatic excursion (Figure 12).⁶⁹ A diaphragm thickening of less than 20% is proposed to be the cut-off for paralysis. Normal diaphragmatic excursion is greater than 2.5 cm (mean 3–5 cm, range 2–10 cm), but excursion of less than 3 cm is fairly frequent.^{8,70–75} Unequal excursion of the hemidiaphragms is common; the difference is usually less than 1.5 cm.^{73,74} Asynchronous motion of the hemidiaphragms is not unusual.^{73,76,77} M mode can also evaluate diaphragmatic velocity, which is correlated with muscle strength (Figure 12). Decrease diaphragm excursion on M mode has been shown to predict weaning failure equal to the rapid shallow breathing index.⁷⁸

Similar to most institutions, our fluoroscopic protocol is typically performed with the patient erect, but occasionally supine positioning is used as it stresses the diaphragm by removing the aid of gravity during inspiration and may increase the sensitivity of the test. The unilaterally paralyzed hemidiaphragm

Figure 14. Posteroanterior (a) radiograph demonstrates an abnormal opacity along the cardiophrenic angle. Axial (b) CT reveals a heterogeneously enhancing mass centered on the anterior right hemidiaphragm with underlying mass effect on the liver. Final pathology is rhabdomyosarcoma.

The appearance of soft tissue tumors on cross-sectional imaging is usually nonspecific. Furthermore, because the diaphragm is a thin structure, the diaphragmatic origin of a mass may be difficult to confirm. Pulmonary, pleural, or abdominal are

far more common than primary diaphragm tumors so suspicion for metastasis should be high when encountering a diaphragm lesion. Thoracic or abdominal tumors may secondarily involve the diaphragm by direct extension.⁷ However, if thoracic or abdominal masses abut the diaphragm without traversing it on imaging studies, definitive diagnosis of invasion cannot be made.

CONCLUSION

Advancements in imaging have improved diagnosis of and aided in treatment of complicated diaphragmatic derangements. Increased awareness and recognition of what each imaging modality has to offer and familiarity with characteristic radiologic findings is crucial in diagnosis, guiding management and preventing complications in this population.

ACKNOWLEDGEMENTS

We would like to acknowledge Ms Sonia Watson and Andrea Moran for their editorial contributions as well as Dr James Zheng from University of Saskatchewan for supplying figure 12.

REFERENCES

- Mayer S, Metzger R, Kluth D. The embryology of the diaphragm. *Semin Pediatr Surg* 2011; **20**: 161–9. doi: <https://doi.org/10.1053/j.sempedsurg.2011.03.006>
- Nason LK, Walker CM, McNeeley MF, Burivong W, Fligner CL, Godwin JD. Imaging of the diaphragm: anatomy and function. *Radiographics* 2012; **32**: E51–E70. doi: <https://doi.org/10.1148/rg.322115127>
- Goumy C, Gouas L, Marceau G, Coste K, Veronese L, Gallot D, et al. Retinoid pathway and congenital diaphragmatic hernia: hypothesis from the analysis of chromosomal abnormalities. *Fetal Diagn Ther* 2010; **28**: 129–39. doi: <https://doi.org/10.1159/000313331>
- Clugston RD, Zhang W, Greer JJ. Early development of the primordial mammalian diaphragm and cellular mechanisms of nitrofen-induced congenital diaphragmatic hernia. *Birth Defects Res A Clin Mol Teratol* 2010; **88**: 15–24. doi: <https://doi.org/10.1002/bdra.20613>
- You LR, Takamoto N, Yu CT, Tanaka T, Kodama T, Demayo FJ, et al. Mouse lacking COUP-TFII as an animal model of Bochdalek-type congenital diaphragmatic hernia. *Proc Natl Acad Sci U S A* 2005; **102**: 16351–6. doi: <https://doi.org/10.1073/pnas.0507832102>
- White JJ, Suzuki H. Hernia through the foramen of Bochdalek: a misnomer. *J Pediatr Surg* 1972; **7**: 60–1. doi: [https://doi.org/10.1016/0022-3468\(72\)90405-8](https://doi.org/10.1016/0022-3468(72)90405-8)
- Tarver RD, Conces DJ, Cory DA, Vix VA. Imaging the diaphragm and its disorders. *J Thorac Imaging* 1989; **4**: 1–18. doi: <https://doi.org/10.1097/00005382-198901000-00007>
- Fraser RG. *Synopsis of diseases of the chest*. 2nd ed. Philadelphia, USA: WB Saunders; 1994.
- Kirks DR, Caron KH. Gastrointestinal tract. In: Kirks DR, ed. *Practical pediatric imaging*. Boston, USA: Little Brown; 1991.
- Benacerraf BR, Greene MF. Congenital diaphragmatic hernia: US diagnosis prior to 22 weeks gestation. *Radiology* 1986; **158**: 809–10. doi: <https://doi.org/10.1148/radiology.158.3.3511506>
- Mullins ME, Stein J, Saini SS, Mueller PR. Prevalence of incidental Bochdalek's hernia in a large adult population. *AJR Am J Roentgenol* 2001; **177**: 363–6. doi: <https://doi.org/10.2214/ajr.177.2.1770363>
- Mullins ME, Saini S. Imaging of incidental Bochdalek hernia. *Semin Ultrasound CT MR* 2005; **26**: 28–36. doi: <https://doi.org/10.1053/j.sult.2004.10.006>
- Gale ME. Bochdalek hernia: prevalence and CT characteristics. *Radiology* 1985; **156**: 449–52. doi: <https://doi.org/10.1148/radiology.156.2.4011909>
- Caskey CI, Zerhouni EA, Fishman EK, Rahmouni AD. Aging of the diaphragm: a CT study. *Radiology* 1989; **171**: 385–9. doi: <https://doi.org/10.1148/radiology.171.2.2704802>
- Panicek DM, Benson CB, Gottlieb RH, Heitzman ER. The diaphragm: anatomic, pathologic, and radiologic considerations. *Radiographics* 1988; **8**: 385–425. doi: <https://doi.org/10.1148/radiographics.8.3.3289099>
- Fraser RG. *Synopsis of diseases of the chest*. 3rd ed. Philadelphia, USA: Elsevier; 2005.
- Davis WS, Allen RP. Accessory diaphragm. Duplication of the diaphragm. *Radiol Clin North Am* 1968; **6**: 253–63.
- Wille L, Holthusen W, Willich E. Accessory diaphragm. Report of 6 cases and a review of the literature. *Pediatr Radiol* 1975; **4**: 14–20. doi: <https://doi.org/10.1007/BF00978814>
- Hopkins RL, Davis SH. Haziness of the right hemithorax in a newborn. *Chest* 1988; **94**: 662–3. doi: <https://doi.org/10.1378/chest.94.3.662>
- Kenanoglu A, Tuncbilek E. Accessory diaphragm in the left side. *Pediatr Radiol* 1978; **7**: 172–4. doi: <https://doi.org/10.1007/BF00975442>
- Currarino G, Williams B. Causes of congenital unilateral pulmonary hypoplasia: a study of 33 cases. *Pediatr Radiol* 1985; **15**: 15–24. doi: <https://doi.org/10.1007/BF02387847>
- Becmeur F, Horta P, Donato L, Christmann D, Sauvage P. Accessory diaphragm-review of 31 cases in the literature. *Eur J Pediatr Surg* 1995; **5**: 43–7. doi: <https://doi.org/10.1055/s-2008-1066162>
- Pearson FG, Cooper JD, Ilves R, Todd TR, Jamieson WR. Massive hiatal hernia with incarceration: a report of 53 cases. *Ann Thorac Surg* 1983; **35**: 45–51. doi: [https://doi.org/10.1016/S0003-4975\(10\)61430-0](https://doi.org/10.1016/S0003-4975(10)61430-0)
- Mitsouras D, Liacouras P, Imanzadeh A, Giannopoulos AA, Cai T, Kumamaru KK, et al. Medical 3D printing for the radiologist.

- Radiographics* 2015; **35**: 1965–88. doi: <https://doi.org/10.1148/rg.2015140320>
25. Ward RE, Flynn TC, Clark WP. Diaphragmatic disruption secondary to blunt abdominal trauma. *J Trauma* 1981; **21**: 35–8. doi: <https://doi.org/10.1097/00005373-198101000-00006>
 26. Rodriguez-Morales G, Rodriguez A, Shatney CH. Acute rupture of the diaphragm in blunt trauma: analysis of 60 patients. *J Trauma* 1986; **26**: 438–44. doi: <https://doi.org/10.1097/00005373-198605000-00005>
 27. Voeller GR, Reisser JR, Fabian TC, Kudsk K, Mangiante EC. Blunt diaphragm injuries. A five-year experience. *Am Surg* 1990; **56**: 28–31.
 28. Guth AA, Pachter HL, Kim U. Pitfalls in the diagnosis of blunt diaphragmatic injury. *Am J Surg* 1995; **170**: 5–9. doi: [https://doi.org/10.1016/S0002-9610\(99\)80242-6](https://doi.org/10.1016/S0002-9610(99)80242-6)
 29. Bonatti M, Lombardo F, Vezzali N, Zamboni GA, Bonatti G. Blunt diaphragmatic lesions: imaging findings and pitfalls. *World J Radiol* 2016; **8**: 819–28. doi: <https://doi.org/10.4329/wjr.v8.i10.819>
 30. Kearney PA, Rouhana SW, Burney RE. Blunt rupture of the diaphragm: mechanism, diagnosis, and treatment. *Ann Emerg Med* 1989; **1218**: 1326–30. doi: [https://doi.org/10.1016/S0196-0644\(89\)80270-7](https://doi.org/10.1016/S0196-0644(89)80270-7)
 31. Chen JC, Wilson SE. Diaphragmatic injuries: recognition and management in sixty-two patients. *Am Surg* 1991; **57**: 810–5.
 32. Gelman R, Mirvis SE, Gens D. Diaphragmatic rupture due to blunt trauma: sensitivity of plain chest radiographs. *AJR Am J Roentgenol* 1991; **156**: 51–7. doi: <https://doi.org/10.2214/ajr.156.1.1898570>
 33. Boulanger BR, Milzman DP, Rosati C, Rodriguez A. A comparison of right and left blunt traumatic diaphragmatic rupture. *J Trauma* 1993; **35**: 255–60. doi: <https://doi.org/10.1097/00005373-199308000-00014>
 34. Hood RM. Traumatic diaphragmatic hernia. *Ann Thorac Surg* 1971; **12**: 311–24. doi: [https://doi.org/10.1016/S0003-4975\(10\)65131-4](https://doi.org/10.1016/S0003-4975(10)65131-4)
 35. Wise L, Connors J, Hwang YH, Anderson C. Traumatic injuries to the diaphragm. *J Trauma* 1973; **13**: 946–50. doi: <https://doi.org/10.1097/00005373-197311000-00002>
 36. Lee HY, Yoo SM, Song IS, Yu H, Kim YS, Lee JB, et al. Spontaneous diaphragmatic rupture after vomiting: rapid diagnosis on multiplanar reformatted multidetector CT. *J Thorac Imaging* 2006; **21**: 54–6. doi: <https://doi.org/10.1097/01.rti.0000187435.91513.ba>
 37. Rees O, Mirvis SE, Shanmuganathan K. Multidetector-row CT of right hemidiaphragmatic rupture caused by blunt trauma: a review of 12 cases. *Clin Radiol* 2005; **60**: 1280–9. doi: <https://doi.org/10.1016/j.crad.2005.06.013>
 38. Marchand P. A study of the forces productive of gastro-oesophageal regurgitation and herniation through the diaphragmatic hiatus. *Thorax* 1957; **12**: 189–202. doi: <https://doi.org/10.1136/thx.12.3.189>
 39. Hammer MM, Raptis DA, Mellnick VM, Bhalla S, Raptis CA. Traumatic injuries of the diaphragm: overview of imaging findings and diagnosis. *Abdom Radiol* 2017; **42**: 1020–7. doi: <https://doi.org/10.1007/s00261-016-0908-3>
 40. Desforges G, Strieder JW, Lynch JP, Madoff IM. Traumatic rupture of the diaphragm; clinical manifestations and surgical treatment. *J Thorac Surg* 1957; **34**: 779–97discussion 797–9.
 41. Probert WR, Havard C. Traumatic diaphragmatic hernia. *Thorax* 1961; **16**: 99–113. doi: <https://doi.org/10.1136/thx.16.2.99>
 42. Andrus CH, Morton JH. Rupture of the diaphragm after blunt trauma. *Am J Surg* 1970; **119**: 686–93. doi: [https://doi.org/10.1016/0002-9610\(70\)90240-0](https://doi.org/10.1016/0002-9610(70)90240-0)
 43. Gourin A, Garzon AA. Diagnostic problems in traumatic diaphragmatic hernia. *J Trauma* 1974; **14**: 20–31. doi: <https://doi.org/10.1097/00005373-197401000-00003>
 44. Gurney J, Harrison WL, Anderson JC. Omental fat simulating pleural fluid in traumatic diaphragmatic hernia: CT characteristics. *J Comput Assist Tomogr* 1985; **9**: 1112–4. doi: <https://doi.org/10.1097/00004728-198511000-00022>
 45. Shackleton KL, Stewart ET, Taylor AJ. Traumatic diaphragmatic injuries: spectrum of radiographic findings. *Radiographics* 1998; **18**: 49–59. doi: <https://doi.org/10.1148/radiographics.18.1.9460108>
 46. Murray JG, Caoili E, Gruden JF, Evans SJ, Halvorsen RA, Mackersie RC. Acute rupture of the diaphragm due to blunt trauma: diagnostic sensitivity and specificity of CT. *AJR Am J Roentgenol* 1996; **166**: 1035–9. doi: <https://doi.org/10.2214/ajr.166.5.8615237>
 47. Killeen KL, Mirvis SE, Shanmuganathan K. Helical CT of diaphragmatic rupture caused by blunt trauma. *AJR Am J Roentgenol* 1999; **173**: 1611–6. doi: <https://doi.org/10.2214/ajr.173.6.10584809>
 48. Larici AR, Gotway MB, Litt HI, Reddy GP, Webb WR, Gotway CA, et al. Helical CT with sagittal and coronal reconstructions: accuracy for detection of diaphragmatic injury. *AJR Am J Roentgenol* 2002; **179**: 451–7. doi: <https://doi.org/10.2214/ajr.179.2.1790451>
 49. Nchimi A, Szapiro D, Ghaye B, Willems V, Khamis J, Haquet L, et al. Helical CT of blunt diaphragmatic rupture. *AJR Am J Roentgenol* 2005; **184**: 24–30. doi: <https://doi.org/10.2214/ajr.184.1.01840024>
 50. Barker JA, Gavant ML, Hughes CB. Posttraumatic intrapericardial diaphragmatic hernia. *AJR Am J Roentgenol* 1997; **169**: 315–6. doi: <https://doi.org/10.2214/ajr.169.1.9207570>
 51. Reina A, Vidana E, Soriano P, Orte A, Ferrer M, Herrera E, et al. Traumatic intrapericardial diaphragmatic hernia: case report and literature review. *Injury* 2001; **32**: 153–6. doi: [https://doi.org/10.1016/S0020-1383\(00\)00151-0](https://doi.org/10.1016/S0020-1383(00)00151-0)
 52. Israel RS, Mayberry JC, Primack SL. Diaphragmatic rupture: use of helical CT scanning with multiplanar reformations. *AJR Am J Roentgenol* 1996; **167**: 1201–3. doi: <https://doi.org/10.2214/ajr.167.5.8911180>
 53. Leung JC, Nance ML, Schwab CW, Miller WT. Thickening of the diaphragm: a new computed tomography sign of diaphragm injury. *J Thorac Imaging* 1999; **14**: 126–9.
 54. Bergin D, Ennis R, Keogh C, Fenlon HM, Murray JG. The “dependent viscera” sign in CT diagnosis of blunt traumatic diaphragmatic rupture. *AJR Am J Roentgenol* 2001; **177**: 1137–40. doi: <https://doi.org/10.2214/ajr.177.5.1771137>
 55. Shanmuganathan K, Mirvis SE, Chiu WC, Killeen KL, Hogan GJ, Scalea TM. Penetrating torso trauma: triple-contrast helical CT in peritoneal violation and organ injury—a prospective study in 200 patients. *Radiology* 2004; **231**: 775–84. doi: <https://doi.org/10.1148/radiol.2313030126>
 56. Hammer MM, Flagg E, Mellnick VM, Cummings KW, Bhalla S, Raptis CA. Computed tomography of blunt and penetrating diaphragmatic injury: sensitivity and inter-observer agreement of CT Signs. *Emerg Radiol* 2014; **21**: 143–9. doi: <https://doi.org/10.1007/s10140-013-1166-0>
 57. Desir A, Ghaye B. CT of blunt diaphragmatic rupture. *Radiographics* 2012; **32**: 477–98. doi: <https://doi.org/10.1148/rg.322115082>
 58. Chiu WC, Shanmuganathan K, Mirvis SE, Scalea TM. Determining the need for laparotomy in penetrating torso trauma: a prospective study using triple-contrast enhanced abdominopelvic computed tomography. *J Trauma* 2001; **51**: 860–9. doi: <https://doi.org/10.1097/00005373-200111000-00007>
 59. Dissanaik S, Griswold JA, Frezza EE. Treatment of isolated penetrating flank trauma. *Am Surg* 2005; **71**: 493–6.

60. Shanmuganathan K, Mirvis SE, White CS, Pomerantz SM. MR imaging evaluation of hemidiaphragms in acute blunt trauma: experience with 16 patients. *AJR Am J Roentgenol* 1996; **167**: 397–402. doi: <https://doi.org/10.2214/ajr.167.2.8686615>
61. Iochum S, Ludig T, Walter F, Sebbag H, Grosdidier G, Blum AG. Imaging of diaphragmatic injury: a diagnostic challenge? *Radiographics* 2002; **22 Spec No**: S103–S116. doi: https://doi.org/10.1148/radiographics.22.suppl_1.g02oc14s103
62. Bowley DM, Grace KL, Hughes PM, Hosie KB, Mayer AD. Rupture of the right hemidiaphragm with liver herniation. *J Trauma* 2002; **52**: 411. doi: <https://doi.org/10.1097/00005373-200202000-00037>
63. Basso SM, Caratozzolo E, Massani M, Antoniutti M, di Pinto FC, Callegari P, et al. Nocturnal dyspnea in a young adult male patient: a typical case of an unrecognized traumatic rupture of the diaphragm. *J Trauma* 2004; **56**: 720. doi: <https://doi.org/10.1097/01.TA.0000078690.12080.23>
64. Somers JM, Gleeson FV, Flower CD. Rupture of the right hemidiaphragm following blunt trauma: the use of ultrasound in diagnosis. *Clin Radiol* 1990; **42**: 97–101. doi: [https://doi.org/10.1016/S0009-9260\(05\)82076-8](https://doi.org/10.1016/S0009-9260(05)82076-8)
65. Reid WD. Respiratory muscle pathology. In: Roussos C, ed. *The thorax*. New York, USA: Marcel Dekker; 1995.
66. Ingram RH. Disease of the pleura, mediastinum, and diaphragm. In: Braunwald E, Isselbacher KJ, Petersdorf RG, Wilson, Martin, Fauci, eds. *Harrison's principles of internal medicine*. New York, USA: McGraw-Hill; 1987.
67. Efthimiou J, Butler J, Woodham C, Benson MK, Westaby S. Diaphragm paralysis following cardiac surgery: role of phrenic nerve cold injury. *Ann Thorac Surg* 1991; **52**: 1005–8. doi: [https://doi.org/10.1016/0003-4975\(91\)91268-Z](https://doi.org/10.1016/0003-4975(91)91268-Z)
68. Hassoun PM, Celli BR. Bilateral diaphragm paralysis secondary to central von Recklinghausen's disease. *Chest* 2000; **117**: 1196–9. doi: <https://doi.org/10.1378/chest.117.4.1196>
69. Sarwal A, Walker FO, Cartwright MS. Neuromuscular ultrasound for evaluation of the diaphragm. *Muscle Nerve* 2013; **47**: 319–29. doi: <https://doi.org/10.1002/mus.23671>
70. Alexander C. Diaphragm movements and the diagnosis of diaphragmatic paralysis. *Clin Radiol* 1966; **17**: 79–83. doi: [https://doi.org/10.1016/S0009-9260\(66\)80128-9](https://doi.org/10.1016/S0009-9260(66)80128-9)
71. Simon G, Bonnell J, Kazantzis G, Waller RE. Some radiological observations on the range of movement of the diaphragm. *Clin Radiol* 1969; **20**: 231–3. doi: [https://doi.org/10.1016/S0009-9260\(69\)80181-9](https://doi.org/10.1016/S0009-9260(69)80181-9)
72. Harris RS, Giovannetti M, Kim BK. Normal ventilatory movement of the right hemidiaphragm studied by ultrasonography and pneumotachography. *Radiology* 1983; **146**: 141–4. doi: <https://doi.org/10.1148/radiology.146.1.6849035>
73. Gierada DS, Curtin JJ, Erickson SJ, Prost RW, Strandt JA, Goodman LR. Diaphragmatic motion: fast gradient-recalled-echo MR imaging in healthy subjects. *Radiology* 1995; **194**: 879–84. doi: <https://doi.org/10.1148/radiology.194.3.7862995>
74. Young DA, Simon G. Certain movements measured on inspiration-expiration chest radiographs correlated with pulmonary function studies. *Clin Radiol* 1972; **23**: 37–41. doi: [https://doi.org/10.1016/S0009-9260\(72\)80132-6](https://doi.org/10.1016/S0009-9260(72)80132-6)
75. Armstrong P, Wilson AG, Dee P, Hansell DM. *Imaging diseases of the chest*. 2nd ed. St. Louis, USA: Mosby; 1995.
76. Juhl JH. Diseases of the pleura, mediastinum, and diaphragm. In: Juhl JH, Crummy AB, eds. *Paul and Juhl's essentials of radiologic imaging*. Philadelphia, USA: JB Lippincott; 1987.
77. Felson B. *Chest roentgenology*. Philadelphia, USA: WB Saunders; 1973.
78. Kim WY, Suh HJ, Hong SB, Koh Y, Lim CM. Diaphragm dysfunction assessed by ultrasonography: influence on weaning from mechanical ventilation. *Crit Care Med* 2011; **39**: 2627–30. doi: <https://doi.org/10.1097/CCM.0b013e3182266408>
79. Higenbottam T, Allen D, Loh L, Clark TJ. Abdominal wall movement in normals and patients with hemidiaphragmatic and bilateral diaphragmatic palsy. *Thorax* 1977; **32**: 589–95-09ENG-. doi: <https://doi.org/10.1136/thx.32.5.589>
80. Kreitzer SM, Feldman NT, Saunders NA, Ingram RH. Bilateral diaphragmatic paralysis with hypercapnic respiratory failure. A physiologic assessment. *Am J Med* 1978; **65**: 89–95.
81. Malagari K, Fraser RG. Imaging of the chest wall and diaphragm. In: Roussos C, ed. *The thorax*. New York, USA: Marcel Dekker; 1995. pp. 1763–837.
82. Chen IY, Armstrong JD. Value of fluoroscopy in patients with suspected bilateral hemidiaphragmatic paralysis. *AJR Am J Roentgenol* 1993; **160**: 29–31. doi: <https://doi.org/10.2214/ajr.160.1.8416639>
83. Wilcox PG, Paré PD, Pardy RL. Recovery after unilateral phrenic injury associated with coronary artery revascularization. *Chest* 1990; **98**: 661–6. doi: <https://doi.org/10.1378/chest.98.3.661>
84. Kim MP, Hofstetter WL. Tumors of the diaphragm. *Thorac Surg Clin* 2009; **19**: 521–9. doi: <https://doi.org/10.1016/j.thorsurg.2009.08.007>
85. Akinci D, Akhan O, Ozmen M, Ozkan OS, Karcaaltincaba M. Diaphragmatic mesothelial cysts in children: radiologic findings and percutaneous ethanol sclerotherapy. *AJR Am J Roentgenol* 2005; **185**: 873–7. doi: <https://doi.org/10.2214/AJR.04.1590>
86. Olafsson G, Rausing A, Holen O. Primary tumors of the diaphragm. *Chest* 1971; **59**: 568–70. doi: <https://doi.org/10.1378/chest.59.5.568>
87. Koyama S, Araki M, Suzuki K, Fukutomi H, Maruyama T, Mun Y, et al. Primary diaphragmatic schwannoma with a typical target appearance: correlation of CT and MR imagings and histologic findings. *J Gastroenterol* 1996; **31**: 268–72. doi: <https://doi.org/10.1007/BF02389529>
88. Itakura M, Shiraishi K, Kadosaka T, Matsuzaki S. Chondroma of the diaphragm-report of a case. *Endoscopy* 1990; **22**: 276–8. doi: <https://doi.org/10.1055/s-2007-1012870>
89. Buckley KM, Whitman GJ, Chew FS. Diaphragmatic pheochromocytoma. *AJR Am J Roentgenol* 1995; **165**: 260. doi: <https://doi.org/10.2214/ajr.165.2.7618536>
90. Posniak HV, Keshavarzian A, Jabamoni R. Diaphragmatic endometriosis: CT and MR findings. *Gastrointest Radiol* 1990; **15**: 349–51. doi: <https://doi.org/10.1007/BF01888817>
91. Pazzini L, La Magra C, D'Agata A, Magnolfi A, Cacchiarelli M, Gotti G. A rare case of malignant diaphragmatic hemangiopericytoma in a patient with pleural effusion. *J Cardiovasc Surg* 2006; **47**: 367–9.