ANATOMY, PHYSIOLOGY, AND MEASUREMENT OF PHYSIOLOGIC FUNCTION FOR COLORECTAL SURGERY

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Solid surgical decision making and operative planning are the cornerstones of excellence in outcomes and performance. Beyond the knowledge of the pathologic process, they require an in-depth understanding of the anatomy and physiology of the area impacted by disease or dysfunction. The embryology and anatomy, as well as the physiology of the appendix, colon, rectum, and anus, are reviewed here, with a particular focus on their impact on surgical evaluation and decision making.

Embryology

The gastrointestinal tract embryologically is derived from the endoderm, which folds into a tubular structure and differentiates into the foregut, midgut, and hindgut to form the respective epithelia and parenchymatous tissues of the visceral and thoracic organs. Their muscular and connective tissue components are derived from the mesoderm. On both ends of the endoderm, fusion zones need to form to provide the connection with the ectoderm. Located on its cephalad oral end is the stomatodeum; on the caudad aboral end is the proctodeum.

The development of the embryonic midgut, hindgut, and cloaca begins in the fourth week of gestation. Each of these embryologic structures is supplied by and grows around a major vascular pedicle; these later become landmarks in the completed anatomy [see Table 1]. The definitive anatomy evolves from axial growth (elongation), radial growth (budding of parenchymatous organs), rotation, and timely fusion. The genetic machinery, which is anything but understood in detail, enacts the construction blueprint with unparalleled precision. However, congenital abnormalities occur when some of these multiple steps fail to complete [see Table 2].

The epithelia of the small bowel, appendix, ascending colon, and the proximal two thirds of the transverse colon are derived from the midgut. The vascular supply to the midgut forms the superior mesenteric artery (SMA). In the sixth week of gestation, the midgut temporarily herniates outside the abdominal cavity and rotates 270° in counterclockwise direction around the SMA [see Figure 1]; later, in week 10, it returns to the abdominal cavity.

The inferior mesenteric artery (IMA) provides the blood supply to the hindgut, which is the origin for the distal transverse colon, the descending and sigmoid colon, the rectum, and the proximal anus. The distal anus is derived from ectoderm and receives its blood supply from the internal pudendal artery. The dentate line marks the divide between the endoderm-based hindgut and the ectodermal anal canal. Before the terminal end of the hindgut develops into separate structures and ostia, its blind end forms a primitive cloaca, which is separated by the cloacal membrane from the ectodermal surface depression of the proctodeum. The cloaca gives rise to the urogenital and digestive system. The descent of the urorectal septum divides the cloaca into the urogenital sinus and the anorectal pouch.

Abnormalities in the development of the urorectal septum most commonly result in anorectal malformations (ARMs). Seventy percent of ARMs are associated with congenital abnormalities of other organ systems. The most common anomalies involve the urogenital system and spine/spinal cord.

Colon

GENERAL CHARACTERISTICS

The colon measures approximately 150 cm in length. Length of instrument insertion during colonoscopy, however, is a rather unreliable parameter for orientation and for the same location may be quite different during insertion versus withdrawal; more definitive landmarks or tattooing are therefore necessary for correct identification of a site of pathology prior to surgical resection. The colon diameter is very variable but generally largest at the cecum (6 to 8 cm) and decreases along its course to the sigmoid colon (2.5 to 4.0 cm). The smaller lumen in conjunction with the more formed stool on the left side and an overall higher incidence of pathology (neoplasm, diverticulitis) are among the factors that conjoin to make the sigmoid a frequent point of large bowel obstruction. Use of a narrow sigmoid for a coloanal anastomosis lacks a sufficient storage capacity and is associated with high-frequency bowel function (low anterior

<table>
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<tr>
<th>Embryologic Precursor</th>
<th>Arterial Supply</th>
<th>Developed Organs</th>
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</thead>
<tbody>
<tr>
<td>Foregut</td>
<td>Celiac artery</td>
<td>Esophagus to ligament of Treitz, including pancreas/liver</td>
</tr>
<tr>
<td>Midgut</td>
<td>Superior mesenteric artery</td>
<td>Ligament of Treitz to proximal two thirds of transverse colon</td>
</tr>
<tr>
<td>Hindgut</td>
<td>Inferior mesenteric artery</td>
<td>Distal third of transverse colon to proximal anus</td>
</tr>
</tbody>
</table>
resection syndrome); creation of a lower pressure reservoir (e.g., by means of a colonic J pouch) has been advocated and may prove beneficial in the first 12 to 24 months.

The colonic wall consists of five layers: mucosa, submucosa, muscularis propria, adventitia, and serosa. In a clinical setting, the wall architecture is best visualized by means of endorectal or endoscopic ultrasonography. Five separate layers can be distinguished as concentric rings: interface/contact zone (inner white), mucosa and muscularis mucosae (inner black), submucosa (middle white), muscularis propria (outer black), and adventitia/fat (outer white) [see Figure 2].

The strongest layer is the submucosa, followed at a distance by the muscularis propria, both of which must be included in any bowel anastomosis to provide adequate strength. The depth of tumor invasion into the bowel wall is the basis for the T stage and an integral part of colon cancer staging according to the TNM system by the American Joint Commission on Cancer (AJCC). In contrast to the small bowel, the colorectal mucosa does not form any villi but consists of crypts that are lined up back to back and are covered by a single layer of cylindrical cells. Intertwined are mucus-producing goblet cells that increase in number toward the rectum. There is a natural cell turnover within 4 to 8 days, during which new cells are built at the base of the crypt and migrate to the surface, where they are shed off. Under healthy circumstances, the interstitium between the crypts is very thin and contains only a limited number of cells, none of which should be polymorphonuclear white blood cells.

Tenia coli, haustra, and appendices epiploicae are defining characteristics of the colon. The outer longitudinal muscle is separated into three teniae coli that travel along the anterior wall of the entire colon. The teniae conjoin on the cecum at the appendiceal base and broaden and coalesce at the rectum. During a sigmoid resection for diverticulitis, the convergence of the teniae signals the minimal distal resection margin that should be obtained as otherwise there is a much higher risk of recurrent attacks.

The colonic haustra are functional segmentations of the colon that result in its characteristic sacculated gross appearance. On radiologic imaging, this haustriation of the colon allows for distinction from the small bowel, which shows plicae circulares and less of a diameter variation. It should be noted, however, that disuse colitis or “burned-out” ulcerative colitis characteristically result in a loss of haustra (lead pipe appearance).

### Table 2: Embryologic Development and Related Malformations

<table>
<thead>
<tr>
<th>Embryologic Step</th>
<th>Normal Anatomy</th>
<th>Malformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>270° counterclockwise rotation</td>
<td>Transverse colon passing over root of small bowel</td>
<td>Partial or complete malrotations</td>
</tr>
<tr>
<td>Return of temporary herniation</td>
<td>Intact abdominal wall</td>
<td>Meckel diverticulum, omphalocele, urachal cyst</td>
</tr>
<tr>
<td>Fusion of endoderm, cloacal membrane, ectoderm</td>
<td>Formation of anus and urogenital system</td>
<td>Imperforate anus, congenital cloaca, congenital rectovaginal/urinary fistula</td>
</tr>
<tr>
<td>Proximodistal migration of neural crest cells</td>
<td>Autonomic innervation</td>
<td>Hirschsprung disease</td>
</tr>
</tbody>
</table>

Figure 1 Malrotation syndrome (on small bowel follow-through with barium contrast).

Figure 2 Colon/rectal wall layers on ultrasound.
The external colon surface has varying degrees of appendices epiploicae, which are serosa-covered pedunculated fat pads; they are most prevalent toward the left colon and more evident in the completely intraperitoneal colon segments (transverse and sigmoid colon) and reflect the patient’s body and fat habitus. Inflammation, torsion, or ischemia of these appendices (characteristically in middle-aged individuals) can occasionally result in epiploic appendagitis with sudden onset of diffuse or localized abdominal pain and among other differential diagnoses may mimic acute appendicitis or diverticulitis. On a computed tomographic (CT) scan, however, there is no or little colonic wall thickening but characteristically a paracolic, rim-enhanced ovoid structure with paracolic fat stranding. The pathology is a self-limited process that usually resolves within 5 days and does not require any surgical intervention.

**Clinical Impact: Assessment of Colonic Anatomy**

For many conditions, the exact configuration of the colon has little clinical impact. Excessive tortuosity (dolichocolon) may be a challenge for a colonoscopy but otherwise does not represent a condition that per se would require any treatment. Colonoscopy with direct visualization of the mucosa as the most frequent source of pathology remains the evaluation of choice. However, before carrying out a surgical intervention, it is mandatory to know the exact location of a pathology, and it may be necessary to have an understanding of the colon configuration (road map). If the location of a pathology cannot be seen on cross-sectional imaging because it is too small (e.g., a relatively small tumor), the tool to define the location consists of endoscopic tattooing of the area. An effort should be made to inject the India ink transmurally such that it becomes visible on the serosal side during the surgery (which, in the case of laparoscopy, lacks the tactile sensation). For gross anatomy, a single-column contrast enema is sufficient but will not provide structural mucosal details. A well-done barium-air double-contrast enema or CT colonography can provide that detail [see Figure 3].

**Appendix**

The appendix vermiformis, as the name suggests, is a narrow, wormlike structure with all histologic layers of a bowel wall; the base of the appendix is located at the otherwise blind apex of the cecum, where the colonic teniae join to form a continuous longitudinal muscular layer. The average length of the appendix is 9 cm (2 to 20 cm), a diameter less than 6 mm, and wall thickness less than 3 mm. The location of the base of the appendix is fairly constant within the variability of the cecal position (which may change due to its floppiness or due to gravidity); the site of the appendix tip, however, varies considerably but seems not to have undergone any major reevaluation since 1933, when 67.5% were reported to be retrocecal, 31% descending pelvic, 1% preileal, and 0.5% retroileal. In the preimaging era, this inconsistency was a major challenge as it was associated with blurring of the classic symptoms of appendicitis (epigastric dull pain, migrating to and becoming more sharp in the right lower quadrant) toward atypical presentations, with pain locations ranging from the right lower quadrant to the right flank, suprapubic area, or right upper quadrant. Nowadays, the diagnosis of acute appendicitis relies on a combination of symptoms, clinical signs, and cross-sectional imaging (CT, magnetic resonance imaging [MRI], or ultrasonography), which aim at identifying an increase in wall thickness and/or diameter along with periappendiceal fat stranding, possibly abscess formation. The gravid uterus adds even more complexity as it elevates the cecum and appendix out of the pelvis and hence causes a gradual shift of abdominal pain into the right upper quadrant and flank region while limiting the use of harmful radiation-based diagnostics.

Anatomic structures adjacent to the appendix include the mesoappendix with the appendicular artery (an end branch of the ileocolic artery) and vein. The ligament (or fat pad) of Treves is a nearly bloodless peritoneal ileocecal fold that extends on the antimesenteric side of the terminal ileum to the base of the appendix. Dissecting through this ligament allows bloodless access to the base of the appendix during appendectomy.

The biological function of the appendix is not entirely understood, but it contains gut-associated lymphoid tissue (GALT) and appears to participate in immune functions of the colon. The lymphoid tissue aids in maturing B...
lymphocytes and produces IgA antibodies.29 The appendiceal epithelium secretes 2 to 3 mL of luminal mucin per day. More recently, it has been proposed that the appendix releases an extracellular matrix, “biofilm,” made of secretory IgA and mucin that could play an important role in the “microbial ecology” of the gut.19,25 The biofilm supports the growth of colonies of bacteria within the colon and serves as a protective barrier to infection.24,25 The loss of the appendix after an appendectomy has not been shown to have any negative immunologic repercussions, even though some data suggest that appendectomy before reaching adulthood may be associated with a reduced incidence of ulcerative colitis.26–29

Cecum

The cecum is the first part of the colon but, strictly speaking, not within the continuity of the fecal stream but rather a side street in the form of a blind-end pocket downward from the ileocecal valve. For that reason, it is not uncommon during colonoscopy to find the cecum less well cleaned out than the rest of the colon, an observation that in itself can add to the orientation. The cecum is either partially or completely peritonealized and measures approximately 6 cm in length.7 With an average of up to 8 cm diameter, it is the widest part of the colon and—following Laplace’s law of physics (tension = pressure × radius)—carries the highest risk of a perforation during states of increased colonic distention (large bowel obstruction), particularly when the ileocecal valve is competent and hence creates a closed-loop obstruction.30 Clinically or on imaging, a dynamic of a rapid progression of the bowel distention to a cecal diameter greater than 10 cm correlates with the threat of a subsequent perforation. Radiographic signs of structural bowel wall impairment include the presence of pneumatosis coli, that is, gas bubbles within the bowel wall. A cecal volvulus (either around its axis or as a volvulus en bascule by folding transversely) is particularly dangerous as the distention is further aggravated by a strangulating component with ensuing ischemia. The management of a patient with a cecal volvulus requires swift action to, most commonly, perform a surgical resection or, on rare occasions, to untwist the torsion and perform a cecopexy.11

Ascending Colon

The ascending colon extends from the ileocecal junction to the hepatic flexure and measures approximately 15 cm in length.31 It is a partially retroperitoneal structure whereby the lateral attachment to the abdominal wall and the peritoneal reflection are marked by the white line of Toldt, the lateral attachment as an inherent retraction tool and needs to be carefully deflected from the mesocolon during the right colon mobilization—either as the traditional lateral-to-medial dissection moves toward the hepatic flexure or as a landmark during the medial-to-lateral approach in laparoscopy—is the duodenum, which is located posteromedial to the hepatic flexure and is generally substantially more caudal than anticipated by many beginning laparoscopists; the structure deserves to be handled with gentleness and needs to be carefully deflected from the mesocolon [see Table 3]. The inferior pole of the right kidney is also positioned below the hepatic flexure. Further medial retraction of the right colon would provide exposure to the inferior vena cava and the root of the mesentery, but that extent is not commonly necessary. The laparoscopic approach has taught us a lot about natural planes to be used for the dissection. The medial-to-lateral approach takes advantage of the lateral attachment as an inherent retraction tool and gains access to the retroperitoneal side of the mesocolon by deflecting the duodenum posteriorly.32 At the hepatic flexure, the colon—supported by the hepatocolic ligament—often tracks posteriorly before it turns medially. On mobilizing the hepatic flexure, vigorous medial retraction of the colon can result in bleeding, either from the hepatocolic ligament, the liver itself when there are adhesions between the liver capsule and the colon or its mesentery, or, most dangerously, from vein branches of the superior mesenteric vein.

Transverse Colon

The transverse colon is one of two fully intraperitoneal colon segments. It hangs like a suspension bridge from the hepatic to the often higher splenic flexure and measures approximately 45 cm in length.31 Posterior and medial to the splenic flexure are the pancreas and the duodenum [see Table 3]. The pericolonic spaces (lesser sac) and ligaments seem to be confusing at first but are easily understood if the embryologic development of the peritoneal surface is taken into consideration. After the peritoneal cavity initially surrounds the various organs, the lesser sac forms and bulges between the stomach and the transverse colon to form the gastrocolic ligament and a four-layer “napkin” that hangs from the transverse colon and develops into the omentum. The gastrocolic ligament transitions seamlessly to the greater omentum, where it is attached to the anterior wall of the colon. Mobilization of the transverse colon can be carried out either as omentum sparing or by including the omentum with the resection.11 For the former, the omentum is lifted toward the stomach and gently dissected off the anterior colon wall; for the latter, the gastrocolic ligament is divided, and the omentum is left on the transverse colon. By raising the whole transverse colon cephalad and following the transverse mesocolon, the ligament of Treitz can be found—a practical maneuver during laparoscopic gastric bypass surgeries.

Descending Colon

The left colon mirrors the ascending colon as it again is a partially retroperitoneal structure of approximately 25 cm in
length, extending from the splenic flexure to the beginning of the intraperitoneal sigmoid loop. The lateral peritoneal reflection is marked by the white line of Toldt. As previously mentioned for the right side, the mobilization of the left colon is started by opening the serosa along this line to access the avascular embryologic plane and gently deflect the colon medially. The left ureter lies posterior to the left colon (but medial to the gonadal vessels), traveling toward the bifurcation of the common iliac arteries [see Table 3]. If otherwise difficult to identify, for example, in the setting of severe inflammation or dense adhesions from previous surgery in that area, it is best found as it crosses the iliac vessel; when difficulties are anticipated, placement of ureteral stents may be beneficial and help in reducing the risk of iatrogenic ureteral injury and, should it nonetheless occur, improved recognition.

The dissection follows the avascular plane toward the splenic flexure, which is at a more acute angle, higher, and more posteriorly located than the hepatic flexure. Releasing the splenic flexure may be needed as part of the resection or to provide additional length to reach the pelvis for a low colorectal/coloanal anastomosis. Excessive traction can result in tears of the splenic capsule and parenchyma and trigger severe bleeding. The attachments of the splenocolic ligament need to be carefully released by staying close to the colon wall. To further augment the colon mobility, transsection of the restraining vascular structures (inferior mesenteric artery and vein) may be necessary but could result in a compromised perfusion of the most distal colon segment.

That is not typically a problem as the gained mobility by far outweighs the limited loss of bowel length.

**Sigmoid Colon**

The sigmoid colon is again a fully intraperitoneal colon segment with a free mesocolon. It connects the lower edge of the descending colon with the proximal rectum. The sigmoid is the narrowest section of the colon with an average diameter of 2.5 cm. Its length varies considerably from 15 to 50 cm, which is also associated with a substantial variability of its location such that symptoms emanating from it are not necessarily limited to the left lower quadrant. For example, sigmoid diverticulitis can present with right lower quadrant pain and may be mistaken for acute appendicitis or a gynecologic pathology. A redundant sigmoid colon with a narrow-based mesentery is at an increased risk for volvulizing around its vascular pedicle. The volvulus results in obstruction and strangulation with associated clinical symptoms; the characteristic x-ray image shows a distended loop pointing from the lower left to the right upper quadrant (coffee bean sign); the condition requires swift intervention to untwist and decompress the bowel before irreversible structural damage occurs and/or to perform the necessary resection immediately or during the same hospitalization.

The higher stool consistency, in conjunction with and aggravated by a low-fiber diet and constipation, seems to be associated with muscular hypertrophy; the increased

### Table 3 Principles and Critical Structures during Colorectal Mobilization/Resection

<table>
<thead>
<tr>
<th>Surgical Mobilization</th>
<th>Target</th>
<th>Landmarks</th>
<th>Avoid/At Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right colon</td>
<td>Ileoceleal junction, ileocecal vascular pedicle, right branch of middle colic artery, right half of omentum</td>
<td>Appendix, ileocecal pedicle, white line of Toldt, duodenum, gastrocolic ligament, bifurcation of midcolic artery</td>
<td>Right ureter, duodenum, gastroepiploic vessels, gallbladder/liver, right kidney</td>
</tr>
<tr>
<td>Transverse colon</td>
<td>Both flexures (hepatic/splenic), midcolic artery, variable: omentum</td>
<td>Runoff from SMA, midcolic bifurcation, splenocolic ligament</td>
<td>Duodenum, proximal jejunum, pancreas, SMA, SMV, spleen, liver</td>
</tr>
<tr>
<td>Descending colon</td>
<td>Distal transverse colon, splenic flexure, descendsigmoid junction, IMA vs. left colic artery, left branch of midcolic artery, IMV, left half of omentum</td>
<td>White line of Toldt, splenocolic ligament, IMA, bifurcation into left colic and superior rectal artery, IMV (inferior edge of pancreas)</td>
<td>Pancreas, spleen, left kidney, IMV</td>
</tr>
<tr>
<td>Sigmoid colon</td>
<td>Descendsigmoid junction, upper rectum, IMA vs. superior rectal artery, IMV</td>
<td>White line of Toldt, splenocolic ligament, IMA, bifurcation into left colic and superior rectal artery, IMV (inferior edge of pancreas), presacral fascia, hypogastric nerves</td>
<td>Left ureter, gonadal vessels, iliac artery/vein, hypogastric nerves, presacral fascia, presacral veins, spleen</td>
</tr>
<tr>
<td>Rectum</td>
<td>Midsigmoid to pelvic floor, mesorectum, fascia propria</td>
<td>IMA, bifurcation into left colic and superior rectal artery, IMV (inferior edge of pancreas), presacral fascia, Waldeyer fascia, hypogastric nerves, fascia propria, Denonvilliers fascia, seminal vesicles/prostate, uterus/vagina</td>
<td>Left ureter, gonadal vessels, iliac artery/vein, presacral fascia, presacral veins, hypogastric nerves, nervi erigentes</td>
</tr>
<tr>
<td>Anus (abdomino-perineal resection)</td>
<td>Same as rectum, pelvic floor including sphincters, possibly posterior vaginal wall</td>
<td>Abdominal: same as for rectum, perineal: coccyx, ischial tuberosities, transverse perinei muscle, Foley catheter</td>
<td>Same as for rectum, urethra</td>
</tr>
</tbody>
</table>

IMA = inferior mesenteric artery; IMV = inferior mesenteric vein; SMA = superior mesenteric artery; SMV = superior mesenteric vein.
intraluminal pressure may promote the mucosa and submucosa to herniate outwards at the sites where blood vessels penetrate the muscle layer. As a result, “false diverticula” form (i.e., pockets that do not involve all layers of the bowel wall).13 The thin wall and the anatomic association with the passage of blood vessels explain the two clinical pathologies that may evolve from diverticula: diverticular bleeding and (2) diverticulitis (acute, chronic). Acute diverticulitis develops from a micro- to a macroperforation, and the spectrum of its severity from mild to life threatening appears to be determined by the effectiveness of surrounding structures to conceal the damage.14 The chronic inflammation of sigmoid diverticula can lead to a strictured segment or fistula development to surrounding organs, such as the bladder, uterus, vagina, small bowel, or even skin.

Rectum

GENERAL CHARACTERISTICS

The rectum is the last and partially extraperitoneal segment of the large intestine. The peritoneum covers the upper third of the rectum on its anterior and lateral aspects and extends anteriorly to the middle third, whereas the lower third typically is completely extraperitoneal. The exact length of the rectum has been defined in a variety of ways.14 Obsolete (because too variable) definitions include the position of the peritoneal reflection (which varies around the individual rectum itself and, for example, in patients with rectal prolapse, is typically very low at the pelvic floor) or the level of the sacral promontory (which changes once the rectum is mobilized).14

From a surgical perspective, there are only two acceptable definitions. The best delineation between the sigmoid colon and the beginning of the rectum is the point where the three colonic teniae coalesce into one (rectum).14 Since this can only be visualized intraoperatively and treatment decisions have to be made before surgery and are different for rectal versus sigmoid/colon cancers, the rectum can also be defined by length only [see Table 4]. Locally advanced rectal cancers are commonly treated with neoadjuvant chemoradiation as opposed to sigmoid and other colon cancers, which are treated by surgery first. The National Cancer Institute has therefore defined the rectum as the 12 to 15 cm from the anal verge as measured by a rigid sigmoidoscopy.14,35

The rectum is not a straight tube, but, in a retrograde direction, starts with a posterior curve above the puborectalis sling (ano-rectal angle), after which it follows the concave anterior surface of the sacrum toward the promontory, interrupted in transverse direction by three functional folds (valves of Houston), before it angles sharply at the pelvic entry (rectosigmoid angle).14,36 Awareness of these angulations [see Figure 4] is crucial not only for safe insertion of a rigid instrument (proctoscope or end-to-end anastomosis [EEA] stapler) but also because they lend themselves to sonographic artifacts (false positive pathology) on ultrasonography when the folds are hit tangentially.13 Furthermore, the angulations above the typically tight pelvic floor provide an explanation as to why rectal foreign bodies get lost once their end goes beyond the anal canal and do not typically just come out: they turn and hence get stuck in a direction different from the one needed for evacuation.13

From a surgical and disease behavior perspective, almost nothing in regard to rectal anatomy is as important as a thorough understanding of the pelvic fascias, which represent the anatomic landmarks of a correct surgical dissection.14,38 These planes of tense fibrous tissue delineate virtual pelvic compartments such as the mesorectal envelope. The mesorectal envelope (fascia propria of the rectum) represents an important even though not impenetrable border for the spread of rectal neoplasms. Maintaining the integrity of this compartment during a total mesorectal excision (TME) has been shown to be the key element of improved surgical technique and outcome.26 Damage to the envelope destroys the compartmental integrity and allows cancer cells to either remain unexcised or contaminate the operative field, thus increasing the risk of local recurrence.6 As stated by the College of American Pathologists, the pathologist plays an essential role in assessing the gross appearance of a resection specimen with regard to the fascial integrity.41

The endopelvic fascia covers the entire pelvis and consists of a visceral and a parietal leaf,14 which are separated by an avascular areolar space [see Figure 5]. On the posterior aspect, the visceral fascia (fascia propria) lines the mesorectum, which, on the resected specimen, should have a smooth, shiny, and symmetrical appearance with a bilobar fatty convexity.42,43 The parietal layer of the endopelvic fascia (presacral fascia) covers the sacrum, the midsacral artery (that has a posterior runoff at the aortic bifurcation), and the presacral veins, which are a potential source of severe pelvic bleeding if the mobilization of the rectum is carried out too posteriorly.14,38 The two fascial layers fuse a few centimeters above the coccyx and form Waldeyer fascia.14,44 Complete mobilization of the rectum to the level of the pelvic floor requires sharp division of Waldeyer fascia behind the rectum. On the anterior aspect, Denonvilliers fascia is the extraperitoneal connective tissue layer that begins at the peritoneal reflection and separates the space anterior to the rectum from the prostate/semenal vesicles or posterior vagina, respectively.14,36 Laterally, the rectum does not display such a clear layer of separation but is surrounded by connective and fat tissue containing hypogastric and pelvic nerves as well as the hypogastric blood vessels arising from the pelvic sidewalls. Even though it does not have the histologic elements of a ligament, this tissue—particularly in older nomenclature—was referred to as the “lateral ligaments.”6,14

Although the mesorectum in the upper and midlevel of the rectum has a substantial cross-sectional volume, it narrows down in the distal third as it approaches the pelvic floor. Within the parietal fascial envelope of the mesorectum are terminal branches of the IMA and a limited number of lymph nodes56; under normal circumstances, these lymph nodes are less than 4 to 5 mm and cannot typically be distinguished from the surrounding fat on cross-sectional imaging (such as endorectal ultrasonography, MRI, or CT).56 Inflammation and metastatic disease increase the size and echogenicity (water content) of the lymph nodes, which renders them more detectable during the pretreatment staging for rectal cancer.11,45 Positron emission tomography (PET) may detect increased activity in cell metabolism (uptake of
18F-fluorodeoxyglucose ([FDG]) but generally has a greater impact on detecting distant metastatic disease than on assessment of the local disease.

Identification of the correct fascial layers in the upper and midrectum and of Waldeyer and Denonvilliers fascia in the lower portion is critical to performing a correct TME.43 This specimen-oriented technique involves sharp dissection of the mesorectal envelope along the areolar tissue and under direct vision down to the pelvic floor, whereby the bilateral hypogastric nerves are gently deflected from the fascia propria.46 The TME technique was perfected and promoted by Heald, who in 1979 referred to this avascular plane as the “Holy Plane of Rectal Surgery.”39 Without the addition of radiation, implementation of this technique alone decreased the local recurrence rate from 28% to 8%.46,47 and in a similar or even better magnitude than what the Swedish Rectal Cancer Trial was able to achieve with the addition of radiation (11% with radiation + surgery compared with 27% with surgery alone).48–50 Furthermore, respecting the planes of dissection minimizes the negative impact on the autonomic nerves as the hypogastric nerves are generally visible and preserved on top of the presacral fascia, hence limiting the negative impact on sexual and bladder function.51

**Table 4** Clinical Impact of Anatomic Differences between Colon and Rectum

<table>
<thead>
<tr>
<th>Variable</th>
<th>Colon</th>
<th>Rectum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
<td>Ileoceleal valve</td>
<td>Tenia confl uence or 15 cm from anal verge</td>
</tr>
<tr>
<td><strong>Proximal</strong></td>
<td>Tenia confl uence</td>
<td>Dentate line</td>
</tr>
<tr>
<td><strong>Distal</strong></td>
<td>Partially to completely intraperitoneal segments: T4 tumor → perforation/peritoneal seeding</td>
<td>Partially to completely extraperitoneal: T4 tumor → invasion into other organs</td>
</tr>
<tr>
<td><strong>Gross anatomy</strong></td>
<td>Visceral arteries (SMA/IMA): ischemia possible</td>
<td>Visceral arteries (SMA/IMA) + somatic arteries (internal iliac): ischemia rare</td>
</tr>
<tr>
<td><strong>Blood supply</strong></td>
<td>Portal vein system, metastatic disease → liver</td>
<td>Portal vein system + systemic circulation (via vena cava): metastatic disease → liver/lung</td>
</tr>
<tr>
<td><strong>Venous drainage</strong></td>
<td>Preoperative: no impact</td>
<td>Preoperative: neoadjuvant chemoradiation</td>
</tr>
<tr>
<td><strong>Lymph nodes</strong></td>
<td>Postoperative: adjuvant chemoradiation</td>
<td>Postoperative: adjuvant consolidation chemoradiation</td>
</tr>
<tr>
<td><strong>Lymph drainage</strong></td>
<td>Unidirectional: low risk of local recurrence</td>
<td>Multidirectional: higher risk of local recurrence</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Visceral arteries (SMA/IMA) + somatic arteries (internal iliac): ischemia rare</td>
<td>Mesorectum + fascia propria: fascial planes</td>
</tr>
<tr>
<td><strong>Proximity</strong></td>
<td>Low probability of temporary vs. permanent stoma</td>
<td>Pelvic floor/sphincter</td>
</tr>
</tbody>
</table>

IMA = inferior mesenteric artery; SMA = superior mesenteric artery.
The circumferential radial margin has been recognized as a key prognostic factor for local recurrence after treatment for rectal cancer. Pelvic MRI has evolved as the imaging tool of choice for that purpose [see Figure 6], whereas ultrasonography remains preferred for assessment of the T level. None of the techniques (CT, MRI, ultrasonography, PET) has shown superiority in assessing nodal involvement. PET scans are relevant for detection of distant metastases and differentiation between scar tissue and local recurrence.

Blood Vessels

General Characteristics

The blood supply to the colon originates entirely from the visceral arteries (superior and inferior mesenteric arteries) and drains into the portal vein system [see Figure 7]. In contrast, the rectum also has a substantial component of its blood supply from and to the somatic circulation. As mentioned in the embryology section, the right-sided colon up to a watershed area near the splenic flexure obtains its arterial blood flow from the SMA. After the pancreaticoduodenal branches, the next and second branch of the SMA is the midcolic artery that supplies the transverse colon, that is, paradoxically a bowel segment distal to the more proximally situated small bowel and right-sided colon segments, whose blood supplies branch off more distally from the SMA. With considerable variability, the colonic branches of the SMA include the ileocolic artery (including the appendicular artery), the right colic artery, and the previously mentioned middle colic artery.

The IMA supplies the left-sided colon from the splenic flexure watershed area to the rectum and a portion of the anus. The IMA splits into the left colic artery (supplying the splenic flexure and the left colon) and the superior hemorrhoidal/rectal artery to the rectosigmoid and proximal anus. The superior and inferior mesenteric artery systems are connected through a limited number of collaterals of variable strength: the arc of Riolan connects the superior and inferior mesenteric arteries more centrally, whereas the marginal artery runs close to the edge of the colon. Due to a relatively limited collateralization, watershed areas are found at the interface of two major arterial supply areas and are the characteristic locations for ischemic events: the most notorious is at the splenic flexure: the Griffith point, which reflects the watershed area between the SMA and the IMA, where the marginal artery of Drummond is small and fine (or sometimes absent). It is important not to create a transverse colostomy at the splenic flexure due to its tenuous blood supply. Of historical significance, Sudeck described a critical point (1906) at the rectosigmoid junction that would be prone to ischemia; however, in 1956, Griffith refuted this by showing that there are collaterals between the two systems.

The rectum receives a triple blood supply and hence is much less frequently affected by ischemia. The superior hemorrhoidal/rectal artery, a branch of the IMA, is the main arterial source to the rectum. The middle and inferior hemorrhoidal/rectal arteries reach the distal rectum and anus. They both originate from the internal iliac artery, either directly (middle) or indirectly via the internal pudendal artery that travels through the Alcock canal (inferior).

The venous map in the periphery follows the arterial supply but centrally has a distinct difference as the visceral blood flow is redirected through the portal system to the liver. The course of the inferior mesenteric vein separates from the IMA and drains into the splenic vein at the lower edge of the pancreas. The superior mesenteric vein conjoins with the splenic vein to form the portal vein. The venous drainage of the rectum follows both a visceral and a systemic pattern: the superior hemorrhoidal vein drains into the inferior mesenteric vein, whereas the middle and inferior hemorrhoidal veins drain through the internal iliac vein into the inferior vena cava and systemic circulation.

Clinical Impact: Assessment of Vascularization

Even though bleeding remains one of the core symptoms in colon and rectal pathology, direct assessment of the vascularization is only rarely necessary. The arterial side might become relevant in (1) massive lower gastrointestinal bleeding for diagnostic and therapeutic indications (e.g., embolization) or (2) to define the perfusion anatomy either after a previous surgical intervention of uncertain details or (3) when chronic or intermittent visceral ischemia is suspected. The venous side, due to the wide collaterals, is rarely affected and only if there is a fairly central impairment of the blood return, for example, by portal vein or complete vena cava thrombosis.

The assessment tools include interventional angiography (with potential embolization) or magnetic resonance angiography if the specifics of vascularization need to be addressed. For less detail, evaluation with routine CT scans with intravenous contrast provides some information. Functional flow information can be obtained with duplex ultrasonography.

Lymph Nodes

General Characteristics

Lymph drainage follows the vascular anatomy with associated lymph nodes. The lymphatic plexus begin in the...
submucosa and extend to the subserosa of the bowel wall. As cancer spreads through access to vascular or lymphatic structures, this is relevant for the management of patients with a “cancerous” polyp. The depth of cancer invasion into the bowel wall (T stage) is directly associated with the probability of having nodal disease. A pT1 cancer (which invades the submucosa but not the muscularis propria) carries a 7 to 10% risk of lymph node metastases. A cancer in a pedunculated polyp that does not reach the basis of the stalk has a lower risk, whereas a flat, “cancerous” polyp is immediately at the level of the lymph vessels and requires appropriate risk analysis. The paracolic or mesorectal lymph nodes, respectively, are the first level; however, there is no exact demarcation as the lymph node levels seamlessly go over to the para-aortic lymph nodes and, in the case of the rectum, also to the lateral pelvic sidewall lymph nodes. The visceral network of lymph vessels is not as strictly organized as in other anatomic regions and hence is less predictable. In regard to the sentinel lymph node concept, which is relevant for breast cancer or melanoma, this particular aspect seems to be reflected in an unacceptably high false negative rate and therefore is one of the key reasons that the methodology used for other cancers has not gained any traction for colorectal cancer.

**Clinical Impact: Assessment of Lymph Nodes**

An oncologic resection should achieve adequate removal of the respective lymph nodes for treatment and for prognostic aspects. A minimum of 12 lymph nodes should be examined and reported (for each vascular segment) to determine proper staging of the tumor. With very few exceptions (e.g., after radiation), a lesser number of nodes may represent either a suboptimal surgery or pathology analysis. Both deficiencies are problematic as they either increase the risk of local recurrence or potentially under-stage the tumor; removal and examination of additional lymph nodes may result in stage migration.
Nervous System

The autonomous enteric nervous system has both sympathetic (inhibitory) and parasympathetic (stimulatory) components. The sympathetic nerves originate at levels T6-L3; the parasympathetic system has two levels that (a) run in the vagal nerve to the small bowel and colon and (b) root in S2-S4 for the pelvic structures. In the bowel wall throughout the entire gastrointestinal tract [see Figure 8], the Auerbach ganglionic plexus is located between the longitudinal and circular smooth muscle layers and regulates its motility.1

The Meissner plexus is located within the inner submucosal layer of the small and large bowel.1 Its function is more multifactorial as it not only regulates bowel motility but is also associated with intestinal blood flow and transport of ions across the intestinal epithelium.1,63

Hirschsprung disease is the result of a defect in the organogenesis when the proximodistal migration of neural crest cells is not completed.64–66 The congenital lack of ganglia (aganglionosis) of the myenteric plexus affects the most distal gastrointestinal tract (rectum, rectosigmoid) and extends proximally to varying degrees.64,67 Deep biopsies are needed to histologically evaluate for the presence or absence of ganglia. It should be noted, however, that even under normal circumstances, there is a short segment of 1 to 2 cm above the dentate line where ganglia may not be detected. Functionally in Hirschsprung disease, however, the internal anal sphincter muscle, which represents the continuation and end of the muscularis propria of the bowel, is always affected and lacks the ability to relax appropriately,64 which is confirmed by the absence of the rectoanal inhibitory reflex (RAIR).

Hirschsprung disease is a disease of childhood or early adulthood, but a few individuals with short segment disease may escape recognition for a long time. Treatment is surgical and consists of resection of the aganglionic distal segment, typically with a pull-through reconstruction.67 The dilated proximal colon (which contains normal ganglia) is commonly preserved except if it has functionally decompensated.

The sympathetic innervation to the rectum is derived from the T6-L3 nerve roots. The superior hypogastric plexus forms behind the IMA and at the sacral promontory branches into two bundles. These are known as the hypogastric nerves that run along both sides behind the fascia propria of the rectum. The parasympathetic nerves from S2-S4 join at the midlevel pelvis and form a less discriminate autonomic nerve plexus that moves from posterior to anterior toward the rectum, bladder, prostate, and uterus.14

Motility

General Characteristics

Colonic motility is complex and not sufficiently understood in detail.68 It depends on an intimate interplay between the enteric ganglia and the nonneural interstitial cells of Cajal.69 The interstitial cells of Cajal (which, in an oncologic context, are the basis for gastrointestinal stromal tumors [GISTs]) are considered pacemaker cells that spontaneously

Figure 8  Colonic wall innervation. ACh = acetylcholine; 5-HT = 5-hydroxytryptamine; NE = norepinephrine.
generate electrical slow waves of rhythmic smooth muscle contractions within the colonic wall. In addition, they transmit signals from enteric neurons to smooth muscle cells of the gastrointestinal tract. Serotonin and gut hormones such as cholecystokinin and other enterohormonal peptides (e.g., vasoactive intestinal peptide, neuropeptide Y, peptide YY, and pancreatic polypeptide) are known to have an impact on intestinal and colonic motility in response to meals or distention, but the details remain a focus of investigation.

In contrast to the propulsive small bowel contractions, the colonic motility varies more and not only serves at propulsing the content but also segments and remixes it. The activity includes tonic contractions, propagating contractions, and nonpropagating (segmenting) contractions whereby the temporal and spatial sequence is of the utmost importance for the effect. The propulsive contractions consist of low-amplitude propagating contractions (also known as rhythmic phasic contractions) and very forceful high-amplitude propagating contractions (also known as giant migrating propulsions). Low-amplitude propagating contractions are random segmental contractions that are single bursts of motility. Giant migrating propulsions start in the ascending colon and serve at moving the stool column toward the rectum, whereby descending inhibition allows for relaxation of the receiving segment.

Colonic motility is stimulated by meals (gastrocolic reflex) and physical activity but also appears to be subject to a diurnal cycle as the activity decreases during sleep and increases on awakening. The latter seems to be the basis for defecatory urge in the morning. The pharmacologic impacts on colonic motility are numerous, complex, sometimes desired, and frequently unwelcome side effects. Opioids negatively impact colonic motility and result in constipation or a delayed return of bowel function after abdominal surgery. Alvimopan and methylnatrexone are two peripherally acting mu-opioid receptor antagonists that do not cross the blood-brain barrier and hence do not impact the central effects of opioids. However, they do block the impact of opioids on colonic and small bowel motility. Alvimopan and methylnaltrexone have been approved for clinical use in postsurgical patient care or opioid-induced constipation, respectively, even though the practical clinical significance beyond statistical significance remains to be tested in view of the additional cost. Neostigmine, a reversible acetylcholine receptor antagonist, has a parasympathetic effect and can be used to stimulate contractions in Ogilvie syndrome. Thoracic epidural anesthesia with a local anesthetic selectively blocks sympathetic nerve roots from T6-L3 and hence shifts the balance toward parasympathetic innervation. The serotonin family appears to increase contractility. Tegaserod, a partial 5-hydroxytryptamine (5-HT₄) receptor agonist, increases the baseline and propulsive contractility of the colon. Prucalopride, a selective, high-affinity serotonin (5-HT₄) receptor agonist with enterokinetic activity, improves colonic motility and stimulates giant migrating propagations. Linaclotide is a new 14–amino acid peptide agonist for the guanylyl cyclase C, which is a transmembranous receptor for heat-stable enterotoxins on the luminal side of intestinal epithelia and triggers secretory diarrhea and increased motility.

**Figure 9** (a) The various types of colonic motility: bidirectional mixing in the proximal colon, unidirectional propagation in the distal colon, and high-amplitude propagated contractions (HAPCs) over several segments. (b) Colonic activity varies with time of day and is most evident on awakening and after meals.

**CLINICAL IMPACT: ASSESSMENT OF COLONIC MOTILITY**

Colonic dysmotility can result in constipation, colonic distention, or diarrhea. In the acute setting (hospital, nursing home, postsurgical), medications, previous surgeries, inactivity, and/or mediastinal or retroperitoneal pathologies are among the frequent triggers of prolonged postoperative ileus (gastric emptying, small bowel) or colonic pseudo-obstruction (Ogilvie syndrome).

In the overwhelming majority of chronic cases, constipation is either caused by poor dietary habits or the result of a morphologic colon obstruction. Management of such
patients requires an age-dependent risk evaluation and respective assessment of the colon as well as coaching on modifications of habits. If those have been checked off and the constipation persists, it may be indicated to initiate functional assessments and test the colonic motility and evacuation:

1. **Clinical evaluation.** A number of instruments have been established and validated to define and quantitate the patient’s constipation symptoms to include the Bristol stool scale, the Rome III criteria for irritable bowel syndrome (IBS), or guidelines to define chronic constipation and other functional disorders.

2. **Colonic transit time.** Qualitative and (semi)quantitative assessment of the unassisted colonic transit time helps distinguish between normal-transit constipation (IBS-C), slow-transit constipation (colonic inertia), or outlet obstruction (pelvic floor dysfunction):
   - a. **Sitzmark study.** Ingestion of radiopaque markers with scheduled x-rays allows for an assessment of the completeness of marker elimination or, in the case of incomplete elimination, distinction of localized versus diffuse distribution patterns [see Figure 10].
   - b. **Scintigraphy with oral radiotisotope markers.** This is an alternative (but more infrastructure-dependent) method to assess the passage of a radioactive swallow.

3. **Morphologic assessment of function.** When clinical symptoms (organ prolapse) or a distal distribution pattern in the Sitzmark study suggest an outlet obstruction pattern, morphologic assessment using dynamic pelvic MRI or defecation proctography may be indicated to delineate the nature of the dysfunction and help distinguish single-compartment prolapse (e.g., isolated rectal prolapse), multicompartament pelvic organ prolapse, enterocele, or paradoxical puborectalis contraction [see Figure 11].

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**Colon Physiology and Metabolism**

**GENERAL CHARACTERISTICS**

The colon does not contribute to the absorption of nutrients. Its two essential functions are to serve as a temporary storage area for the body waste and preserve water and energy. The colon absorbs water and some electrolytes (in

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**Table 5 Mediators and Drugs Affecting Colonic Motility**

<table>
<thead>
<tr>
<th>System</th>
<th>Agent/Drug</th>
<th>Effect</th>
<th>Clinical Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enterohumoral stimulation</td>
<td>CCK, neuropeptide YY, peptide vasoactive</td>
<td>Increased postprandial motility</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>peptide polypeptide, vasoactive intestinal peptide</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parasympathicomimetic</td>
<td>Neostigmine</td>
<td>Increased contraction/motility</td>
<td>Ogilvie syndrome, ileus</td>
</tr>
<tr>
<td>(muscarinic receptors)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sympatholytic</td>
<td>Thoracic epidural anesthesia</td>
<td>Increased motility</td>
<td>Postoperative pain management</td>
</tr>
<tr>
<td>Mu-Opioid antagonist</td>
<td>Alvimopan</td>
<td>Reduced suppression of intestinal activity</td>
<td>Antagonism of postoperative opioid-</td>
</tr>
<tr>
<td>(peripherally restricted)</td>
<td>Methylnaltrexone</td>
<td>Reduced suppression of intestinal activity</td>
<td>based pain management</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Chronic opioid-dependent constipation</td>
</tr>
<tr>
<td>Serotonin 5-HT4 receptor</td>
<td>Cisapride</td>
<td>Increased motility</td>
<td>IBS-C</td>
</tr>
<tr>
<td>agonists</td>
<td>Prucalopride, tegaserod</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloride channel-mediated</td>
<td>Lubiprostone</td>
<td>Secretagogue → accelerated colonic transit</td>
<td>IBS-C, chronic constipation</td>
</tr>
<tr>
<td>secretagogue</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guanylate cyclase-C agonist</td>
<td>Linacotide</td>
<td>Secretagogue → accelerated colonic transit</td>
<td>IBS-C, chronic constipation</td>
</tr>
<tr>
<td>Glucagon</td>
<td>Glucagon, glucagonlike peptide (GLP)</td>
<td>Smooth muscle relaxation</td>
<td>Counteract spasticity during colonoscopy/anastomosis, pediatric intussusception</td>
</tr>
<tr>
<td>Serotonin 5-HT3 antagonist</td>
<td>Ramosetron</td>
<td>Inhibits motility</td>
<td>Withdrawn due to risk of ischemic colitis</td>
</tr>
</tbody>
</table>

CCK = cholecystokinin; 5-HT = 5-hydroxytryptamine; IBS-C = irritable bowel syndrome-constipation.

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Figure 10 Assessment of colonic transit by means of a Sitzmark study.
exchange for others), as well as energy carriers for the colonocytes. The colon, on average, receives 600 to 1,000 mL (on occasion up to 2 L) of effluent from the terminal ileum, of which it reabsorbs 60 to 90%, leaving 100 to 300 mL of water in the stool. As in the body’s other transmembrane translocations of molecules, the colonic mechanism also relies on a combination of passive or active energy-driven differences in ion concentrations that result in an electrochemical gradient across the cell membrane. On the basolateral aspect of the colonocytes (directed to the interstitial space and the blood vessels), a Na+/K+-ATPase pump actively pumps sodium out of the cell with uptake of potassium [see Figure 12]. As a result, the colonocytes maintain a low intracellular sodium concentration such that on the apical membrane directed to the bowel lumen, sodium ions follow the electrochemical gradient and diffuse through sodium channels into the cell. As sodium diffuses into the cell, water follows and is hence absorbed from the feces.

Two additional mechanisms of sodium uptake are the Na+/H+ and Cl-/HCO3⁻ exchange and the Cl-/butyrate exchange. In animals, a Na+/H+ and Cl-/HCO3⁻ exchange is located on the apical surface of the colonocyte and drives net sodium absorption. Sodium and chloride are absorbed into the cell by electrolyte-specific channels in exchange for excretion of HCO3⁻ and H⁺ into the lumen. Whether human cell physiology is comparable to the animal models will have to be determined. The cystic fibrosis transmembrane conductance regulator (CFTR) is a protein channel involved in the physiologic and secretagogue-induced secretion of Cl⁻. In cystic fibrosis patients, the ability to secrete chloride...
is reduced or absent and affects several organ systems. In the gastrointestinal tract, it results in meconium-ileus in 10% of newborns and meconium-equivalent at a later age.81

The Cl−/butyrate exchange is based on short-chain fatty acids (SCFAs) that are believed to stimulate sodium absorption.80,82,83 Butyrate and chloride are absorbed across the membrane, whereas bicarbonate is released.80

The absorption of luminal effluent can be increased up to 5 to 6 L per day, primarily when aldosterone is present.79 Aldosterone stimulates the upregulation of sodium channels on the colonocyte membrane, which allows for increased sodium/water absorption.80,84

The colonocyte obtains 60% of its energy from the luminal content in a symbiotic relationship with intraluminal bacteria. The colon is colonized with over 400 species of bacteria that serve an essential function in colonic metabolism (microbiome).85,86 There are 10^{12} bacteria per gram of wet feces.84 Most of the bacteria are anaerobes, but there are also aerobes and gram-positive and gram-negative bacteria. Bacteroides is the most common anaerobe bacterium and Escherichia coli the most common aerobic bacterium in the colon.

These bacteria ferment insoluble carbohydrates, creating SCFAs, the primary energy source for the colonocyte.79,82 Acetate, propionate, and butyrate are the primary SCFAs.79 Butyrate is the major energy source for the colonocyte, although it accounts for only 20% of all the SCFAs in the colon.80 Furthermore, butyrate is thought to inhibit colonic inflammation and carcinogenesis, decrease oxidative damage to the colonic mucosa, and aid in colonic growth and differentiation.79,80 Absence of SCFAs as a result of fecal diversion results in a loss of mucosal integrity (diversion colitis/proctitis).

**Clinical Impact: Diarrhea**

Diarrhea, defined as too loose or too frequent stools, can be triggered by numerous causes (e.g., infectious, dietary, toxic, pharmacologic, intrinsic/enterohumeral, hypermotility). They result in a number of isolated imbalances or, more frequently, combinations thereof, such as increased motility, exhausted absorptive capacity of the colon (due to excessive volume of small bowel effluent), increased colonic secretion versus insufficient absorption, or physical mucosal damage.79 Heat-stable enterotoxins are able to stimulate the transmembranous receptor guanylyl cyclase C and trigger secretory diarrhea. Non–toxin-producing strands of *Clostridium difficile* are commensal colonic bacteria. However, acquisition of virulent strands producing toxins A (enterotoxic) and/or B (cytotoxic) can result in a broad spectrum of clinical presentations, from asymptomatic carrier, to chronic diarrhea without morphologic abnormality, to pseudomembranous colitis or deadly fulminant colitis.85

**Anal Canal Anatomy**

**General Characteristics**

Definitions of the anal canal vary considerably between anatomists and surgeons.14 The surgical anal canal reflects the digital rectal examination and extends from the anal verge to the upper level of the puborectalis sling; it measures, on average, 2 to 4 cm (with substantial individual and gender variation).14 The anatomic and histologic anal canal entails the distance from the anal verge to the anal transitional zone 6 to 12 mm above the dentate line.14 The microscopic anatomy of the anal canal is defined in relation to the dentate line, which marks the embryologic fusion zone between the endo- and ectoderm. The anal transitional zone (also known as the claccogenic zone) reflects the change from single-layer columnar colonic mucosa to a multilayer cuboidal, transitional, and squamocolumnar pattern.80 The transition zone coincides with a bluish color due to the underlying hemorrhoidal plexus.89 Just below the dentate line, the so-called anoderm has squamous epithelium but lacks skin appendages (hair follicles, apocrine glands) in the first segment.88 Outside the anal verge, skin appendages are present, the epithelium becomes thicker and more pigmented, and the skin creates a radial pattern.89 The term *anal margin* is frequently used but poorly defined and much less needed: it refers to the skin outside the anal verge up to a virtual perimeter border of approximately 5 cm.11,14

Under normal circumstances, the dentate line is located approximately 1 to 2 cm above the anal verge. Correlating with the wide rectal reservoir narrowing to the anal canal, the last segment is characterized by a circumferential arrangement of axial mucosal folds, the columns of Morgagni.14 The anal crypts are located at the base between two adjacent columns (i.e., at the dentate line) and reflect the entry point of the anal glands. These glands, whose function is unknown in humans, are variable in number (four to eight) and traverse the internal anal sphincter to the intersphincteric space.14 These cryptoglandular complexes in the overwhelming majority of cases appear to be the origin of perirectal abscess and fistula formation.

As previously mentioned, the dentate line reflects not only a histologic transition zone but also the border between predominantly visceral and strictly somatic blood supply, lymph drainage, and innervation.11,14 Proximal to the dentate line, the arterial blood supply derives from the superior hemorrhoidal/rectal artery (the terminal branch of the IMA), in conjunction with the much smaller middle hemorrhoidal artery that branches off the internal iliac artery. Submucosal hemorrhoidal plexus forms the hemorrhoidal cushions (internal hemorrhoids) above the dentate line; when not enlarged, these cushions are an important component of the continence mechanism as they add to the fine-tuning of the anal canal seal. Sensory nerve fibers run within the autonomic nerve plexus and transmit signals on bowel distention but to a much lesser degree on pain. For that reason, management of internal hemorrhoids above the dentate line (e.g., banding, stapled hemorrhoidectomy) is associated with comparably less pain.80,91

In contrast, the anal canal distal to the dentate line is supplied by branches of the internal iliac artery only, that is, the middle and inferior hemorrhoidal artery, the latter of which branches off from the internal pudendal artery. The venous drainage follows the arterial supply but has extensive collaterals. The external hemorrhoidal plexus have variable junctions to the internal hemorrhoidal plexus. This area of the anal canal (particularly the skin) is richly innervated by pain fibers, which explains that external pathologies (thrombosed external hemorrhoids, abscess, fissure, surgical wound) are associated with substantial pain.
Lymphatic drainage is also divided at the dentate line: (1) to the mesorectal and pelvic lymph nodes (above the dentate line) and (2) to the inguinal and/or internal iliac lymph nodes (below the dentate line).

CLINICAL IMPACT: DISTINCTION BETWEEN DIFFERENT ANORECTAL CANCERS

Cancer staging and treatment vary considerably between rectal cancer, anal cancer, or “anal margin” cancers:

1. Perianal cancers can be seen in their entirety without instrument help and are assessed and treated as skin cancers.
2. Anal canal cancer (“anal cancer”) refers to tumors of mostly squamous cells but occasionally adenocarcinoma (arising from the anal or skin glands, occasionally from fistulous tracts) whose center and origin appear to be distal to the dentate line and/or that cannot be visualized in their entirety without instrumentation because they are located and at least in part hidden within the anal canal (proximal to the anal verge). The staging follows the TNM guidelines and is based on tumor size (T), lymph node involvement (N), and distant metastases (M) whereby the inguinal lymph nodes are relevant sites of progressive disease.
3. Rectal cancers are mostly adenocarcinoma (rarely adeno-squamous or even squamous cell carcinoma) that originate above the dentate line but with increasing size may expand to and through the anal canal. The staging according to the TNM system is based on depth of invasion (T), perirectal/pelvic lymph node involvement (N), and distant metastases (M).
4. Nonepithelial tumors (melanoma, carcinoid, lymphoma) are assessed and treated according to specific guidelines.

Musculature of the Pelvis

An arrangement of several muscles provides structural support and functional closure of the pelvic and gastrointestinal tract [see Table 6]. They can be divided into (1) muscles that line the sidewalls of the osseous pelvis, (2) muscles of the pelvic floor, and (3) muscles of the anal sphincter complex.14,92

The pelvic floor (pelvic diaphragm) is a composite muscle consisting of several subunits that are innervated by branches of the primary ventral branches of the spinal nerves S3-S4 and form the funnel-shaped musculotendinous termination of the pelvic outlet.14 It supports the abdominal and pelvic organs but allows passage of the anorectal and urogenital viscera through two separate hiatal openings;4,43 furthermore, the pelvic floor is an important component for both control and evacuation processes. Separate units of the levator ani complex are identified from lateral to medial as the ischiococcygeus, iliococcygeus, pubococcygeus, and puborectalis muscles. The anococcygeal raphe, a fibrous condensation, serves as muscle insertion in the posterior midline. The puborectalis muscle has an anterior insertion and forms a U-shaped sling around the upper anal canal (anorectal angle); it is cephalad to and transitions into the deep component of the external anal sphincter muscle; both muscles are innervated by the inferior rectal nerve, a branch of the pudendal nerve.14

The gastrointestinal tube merges into the lowest point of the pelvic floor and forms the cylindrical anal canal with muscle components of the striated skeletal pelvic floor (puborectalis and external sphincter muscles) as well as the smooth muscle visceral muscularis propria; as that layer continues, it condenses to form the internal anal sphincter, which is innervated by autonomic sympathetic (L5) and parasympathetic (S2-S4) nerves. The external anal sphincter is innervated by the inferior pudendal nerve, a branch of S2-S4. The internal anal sphincter ends below the dentate line but before the external sphincter, which results in a palpable intersphincteric groove.11,88

Anorectal Physiology: Continence and Defecation

GENERAL CHARACTERISTICS

Both continence and defecation seem to be simple events but in reality rely on a subtle interplay of structural and functional components.11,14 The peristaltic wave propulses the stool toward the rectum, where it is stored until a defecation is desired and initiated.14 Control relies on a functional and modifiable outlet resistance, which is generated by the previously mentioned muscular structures; in addition, the capacity and compliance of the rectal reservoir (storage area) and the stool consistency are relevant elements. The internal anal sphincter and the combination of external anal sphincter and puborectalis muscle contribute to the generation of the resting pressure at 50 to 80% and 20 to 30%, respectively. On demand, the external anal sphincter and the puborectalis

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Type and Innervation</th>
<th>Function</th>
<th>Contribution</th>
<th>ERUS Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levator ani: ischiococcygeus, iliococcygeus, pubococcygeus, puborectalis</td>
<td>Skeletal/striated</td>
<td>Support of abdominal and pelvic organs, anorectal angle</td>
<td>Anorectal angulation</td>
<td>White (hyperechogenic), parabolic shape</td>
</tr>
<tr>
<td>External anal sphincter muscle</td>
<td>Skeletal/striated, Slow twitch</td>
<td>Involuntary and voluntary</td>
<td>Resting tone</td>
<td>White (hyperechogenic), outer ring, extends from lower end of puborectalis muscle to distal anal canal</td>
</tr>
<tr>
<td>Internal anal sphincter muscle</td>
<td>Smooth muscle</td>
<td>Involuntary</td>
<td>Resting tone</td>
<td>Black (hypoechogenic) inner ring; extends from lower end of puborectalis muscle to midanal canal</td>
</tr>
</tbody>
</table>

ERUS = endorectal ultrasound.
muscle can substantially increase the pressure but typically cannot maintain the incremental squeeze level for more than 1 minute.

Distention in the rectum triggers the involuntary smooth muscles of the internal anal sphincter to relax, while, in response, the external sphincter contracts.44,45 This RAIR is considered a sampling reflex to allow for discrimination between gas, liquid, or solid stool.44 If a defecation is permitted, the puborectalis muscle sling relaxes, hence straightening the anorectal angle; at the same time, Valsalva maneuvers increase the abdominal pressure to support the increased rectal contractility and propulsion. The pelvic floor descends, and both the internal and external anal sphincter muscles relax such that the stool can be evacuated.94 If defecation is to be deferred, the external sphincter and puborectalis muscles contract, hence dramatically increasing the outlet resistance, while the rectum relaxes to accommodate more stool in the rectal vault.44,95

CLINICAL IMPACT: INCONTINENCE AND OBSTRUCTED DEFECATION

Disturbances or imbalances of the three core components of fecal control (stool consistency, rectal reservoir capacity and compliance, functional sphincter complex) may contribute to the development of incontinence.11,44 Alteration of the stool consistency (diarrhea) and volume may overcome the rectal capacity and exhaust the sphincter resistance, leading to fecal incontinence.96 The rectal capacity and compliance may be impaired by proctitis or fibrosis (e.g., inflammatory bowel disease, radiation exposure, surgery).96 Furthermore, the sphincter function can suffer a negative impact through numerous mechanisms (e.g., injury, surgery, nerve damage, degeneration).96 Loss of rectal sensation may represent a localized phenomenon or be part of systemic or regional neuropathy; as a result, the urge to defecate may be diminished.

Pelvic organ malposition and discoordination of the pelvic floor muscles are common pathophysiologic mechanisms to negatively interfere with the normal flow of defecation. Pelvic organ prolapse may cause physical obstructions (intussusception) or result in kinks that are aggravated by positional gravity or Valsalva maneuvers. Functional problems include contraction rather than relaxation of the puborectalis muscle during attempted evacuation, which decreases the anorectal angle and increases the outlet obstruction (obstructed defecation). In the longer run, the chronic spasticity may be associated with chronic pelvic pain (levator ani spasm), which can be replicated by lateral tenderness to palpation on the levator muscles on digital rectal examination.

Anophysiology Testing

GENERAL CHARACTERISTICS

A good history and a physical anorectal examination can often define the nature of a functional problem quite well. Nonetheless, for medical and potentially legal reasons, it might be desirable to obtain objective parameters to support the clinical impression. Anophysiology testing, which consists of a number of modules [see Table 7], aims at analyzing the anorectal function and morphology and defining factors contributing to incontinence and/or constipation41.

<table>
<thead>
<tr>
<th>Test</th>
<th>Purpose</th>
<th>Normal Values</th>
<th>Interpretation</th>
<th>Indication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pudendal nerve motor terminal latency</td>
<td>Nerve conductivity</td>
<td>&lt; 2.5 ms</td>
<td>Pudendal neuropathy?</td>
<td>Potential prognostic parameter for sphincteroplasty</td>
</tr>
<tr>
<td>Manometry</td>
<td>Resting tone</td>
<td>50–100 mm Hg</td>
<td>Absolute values, pressure profile, length, asymmetry</td>
<td>Objective data prior to treatment</td>
</tr>
<tr>
<td>RAIR</td>
<td>Reflex circle</td>
<td>Present</td>
<td>Present = normal; absent = different reasons</td>
<td>Presence → HD and Chagas disease ruled out</td>
</tr>
<tr>
<td>Anorectal volume sensation</td>
<td>Sensory function</td>
<td>FS 10–50 mL</td>
<td>Abnormal/normal volume?</td>
<td>Megarectum/rectocele, strictured/scarred rectum, IBS</td>
</tr>
<tr>
<td>Rectal compliance</td>
<td>Reservoir function</td>
<td>2–6 mL/mm Hg</td>
<td>Abnormal/normal compliance?</td>
<td>Megarectum/rectocele, strictured/scarred rectum, IBS</td>
</tr>
<tr>
<td>EMG</td>
<td>Neuromotor unit</td>
<td>Baseline</td>
<td>Normal sequence, paradoxical contraction</td>
<td>Constipation workup, occasional assessment of sphincter contractility</td>
</tr>
<tr>
<td>Balloon expulsion</td>
<td>Neuromuscular and content</td>
<td>Success</td>
<td>Success vs. failure</td>
<td>May suggest need for defecography or MRI</td>
</tr>
<tr>
<td>ERUS</td>
<td>Normal vs. pathological</td>
<td>Puborectalis sling</td>
<td>Intact, normal thickness, normal echogenicity</td>
<td>Segmental defect? Fragmentation? Scarring?</td>
</tr>
</tbody>
</table>

EAS = external anal sphincter; EMG = electromyography; ERUS = endorectal ultrasonography; FS = first sensation; FU = first urge; HD = Hirschsprung disease; IAS = internal anal sphincter; MRI = magnetic resonance imaging; MTV = maximal tolerable volume; RAIR = rectoanal inhibitory reflex.
1. **Muscle strength.** Anorectal manometry evaluates the tone of the sphincter muscle at rest and during squeezing at multiple levels throughout the anal canal, defines the length and profile of the high-pressure zone, and, on occasion, may provide information about asymmetries as clues for underlying defects.

2. **Neuromuscular function.** Several components can be assessed according to the specific needs and may provide different aspects of information.
   - a. Perianal sensation and anal wink are both part of the clinical examination and can be assessed by means of a cotton swab. They provide basic information about the intactness and symmetry of the innervation.
   - b. Pudendal nerve terminal motor latency (PNTML) measures the conductivity of the pudendal nerve between a stimulus site and the reading site on the sphincter complex; prolonged PNTML is interpreted as a sign of pudendal neuropathy.
   - c. Anorectal volume sensation is assessed by incremental injection of fluid into a rectal balloon to determine the respective volumes for (a) first sensation, (b) first urge to defecate, and (c) the maximal tolerable volume. The volume is typically correlated to the pressure and allows for calculation of the rectal compliance. Excessive volume tolerance may provide a clue to underlying sensory neuropathy; reduced volume tolerance suggests either a diminished or rigid reservoir function (low compliance) or irritable bowel syndrome (low-volume tolerance with normal rectal compliance).
   - d. During RAIR, the rectal balloon is rapidly filled with air to trigger the reflexive relaxation of the internal sphincter. The presence of this reflex rules out Hirschsprung or Chagas disease, whereas its absence is necessary but not sufficient to confirm either diagnosis.
   - e. Anorectal electromyography (EMG) is occasionally used to evaluate neuromuscular motor units of the sphincter complex. It can be carried out either as more precise but also more uncomfortable needle EMG or more commonly as surface EMG that only records the underlying sensory neuropathy; reduced muscle tone suggests either a diminished or rigid reservoir function (low compliance) or irritable bowel syndrome (low-volume tolerance with normal rectal compliance).

3. **Reservoir function.** The storage function of the rectum is assessed by means of the rectal capacity and compliance (see above). Both parameters may have decreased as a result of various disease processes or treatments (surgery, radiation) or increased (e.g., in the presence of a large rectocele or a megarectum).

4. **Evacuatory function.** Balloon expulsion is a very simple and cheap tool to assess the patient’s ability to coordinate the complexity of different defecatory components and eliminate the balloon. In cooperative patients, it helps rule out relevant pelvic floor dyssynergia (i.e., the discoordination of rectum, abdominal, and pelvic floor muscles during defecation).

5. **Morphology.** Anorectal ultrasonography (and less commonly MRI) is performed to assess the integrity of the components of the puborectalis and internal and external sphincters and weaknesses or defects.

**CLINICAL IMPACT: SACRAL NERVE STIMULATION**

Treatment options for fecal incontinence, include, among others, sacral nerve stimulation, which entails a two-stage procedure to continuously stimulate the S3 nerve root. The first stage is primarily for diagnostic and prognostic purposes but already places a lead with four stimulatory subunits into the S3 foramen. Correct placement allows for obtaining a visible motor response on the pelvic floor (bellow sign) and the toes. If this temporary electrode, which is connected to an external stimulator, results in at least 50% improvement in the incontinence symptoms, the second procedure 2 weeks later implants a definitive stimulator. The treatment has been remarkably successful even though the exact mechanism of action remains unclear. It has been speculated that the stimulation modulates the rectal sensation, stimulates and modulates via the afferent pathways the associated brain activity, or potentially initiates a retrograde peristaltic wave.

**Summary**

A thorough understanding of the colorectal and anorectal anatomy and physiology represents the basis for the clinician to develop a meaningful differential diagnosis, define and initiate appropriate tests, and carry out successful surgical interventions. It should be cautioned, however, that the individual settings may vary considerably and that more detailed information may need to be gathered.

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**References**


26. Beaugerie L, Sokol H. Appendicitis, not appendectomy, is protective against ulcerative colitis, both in the general population and first-degree relatives of patients with IBD. Inflamm Bowel Dis 2010;16:356–7.


Acknowledgment

Figures 4, 5, 7, 8, 9, and 12  Karen Williams