I: A New Look at Equine Gastrointestinal Anatomy, Function, and Selected Intestinal Displacements

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Introduction

To truly understand the equine gastrointestinal tract, one has to accept the fact that very likely it was designed by a committee. Most equine practitioners who have dealt with horses with colic accept this fact without hesitation. As a result, the aspiring equine practitioner has to face several rather daunting tasks, namely 1) making sense of the anatomy of the horse's gastrointestinal tract, 2) developing an appreciation for the dynamics of fluid movement into and out of the various portions of the gastrointestinal tract, and 3) developing a working understanding of the variety of intestinal displacements that can occur. In contradistinction to people who readily develop mental 3-dimensional images from written descriptions and 2-dimensional drawings in textbooks, many of us are visual learners who have trouble developing a good mental image of the horse's intestinal tract. In an effort to overcome some of these difficulties and simplify the complexities of the equine gastrointestinal tract, during the past four years we created a series of 3-dimensional computer-generated images of the horse's gastrointestinal tract under normal and abnormal situations.

We have used these 3-dimensional images in an attempt to address a very real problem called cognitive overload,[1] which occurs when a learner (e.g., a practitioner at a continuing education seminar or a veterinary student) is presented material in a manner that interferes with the message being delivered. Therefore, the brain has to do two things at once: interpret the media as well as grasp the concept. As an example, traditional methods of presenting equine gastrointestinal anatomy and disease processes require that a learner's brain transform 2-dimensional diagrams into complex 3-dimensional structures. For many people, this makes it difficult to focus on the important anatomical structures and disease processes and they therefore have difficulty learning the material. To minimize cognitive overload, a technique called scaffolding is used.[2] Scaffolding supports a learner to the extent that the learner is asked to concentrate only on the specific

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Fig. 1. Digital image of the outer shell of the horse.

gap in his/her learning. Scaffolding is achieved by the use of well-sequenced instruction and appropriate instructional media. Our strategy exemplifies scaffolding by using accurate 3-dimensional depictions of the intestinal tract as it sits within the horse's abdominal cavity. We also have strived to represent the anatomic structures that might be palpated during a rectal examination of a horse with specific gastrointestinal abnormalities causing colic, which hopefully will increase the usefulness of the 3-dimensional images.

During the past four years, these computer-generated images have been used in various portions of our veterinary curriculum as well as in continuing education seminars for veterinary practitioners. We have used these images to reinforce basic concepts taught in gross anatomy classes, to provide representations of the fluid fluxes that occur normally in the equine gastrointestinal tract, and to present dynamic animations depicting how some of the more common intestinal displacements might occur. The goal of this article is to highlight how some of these images were created and used to impart the information necessary for developing a basic understanding of the anatomy, physiology, and pathophysiology of the equine gastrointestinal tract.

Materials and Methods

Creating the Transparent Digital Horse

We viewed as our first task the creation of a digital yet realistic and visually appealing horse, complete with 3-dimensional representations of what we considered to be the important anatomical structures within the abdominal cavity. We felt it was essential to portray the abdominal structures from different viewpoints and to create animations depicting some of the more difficult-to-understand intestinal displacements. We therefore needed very high-end computer hardware and software to create the complex 3-dimensional structures. The hardware was initially a Silicon Graphics[a] Impact Indigo2, after which we used a Silicon Graphics Octane 2 dual 400 MHz processor. The software was initially Power Animator[b] and was later improved with Maya 3.0.[b] We utilized a commercially available digital image of a normal horse as the shell to house the abdominal organs (Fig. 1).

We used a combination of approaches to create the abdominal organs, making a special effort to remain as anatomically accurate as possible. For example, one of the artists created a miniature clay model of the various portions of the gastrointestinal tract. We also referred to descriptions and illustrations in a variety of anatomy texts, examined and photographed the abdominal organs of horses on the postmortem floor, and called on the expertise of other faculty members in the College of Veterinary Medicine. In the end, we used artistic license to develop some of the images and animations, primarily as a result of discrepancies/problems encountered in the process (e.g., minor differences in details among the textbooks, many illustrations in textbooks depicting the intestines fully distended rather than in their normal configuration, etc.).

Although our overall aim was to make the various portions of the gastrointestinal tract realistic and, therefore, understandable, we quickly recognized the need to include other structures as landmarks. These included the relevant portions of the horse's axial skeleton, ribs, diaphragm, vena cava, aorta, kidneys, pancreas, liver, and cranial mesenteric artery (Fig. 2). Although some of these structures ended up being deleted from some of the animations, we thought it was necessary to have them all present initially to help orient the novice regarding the relative positions of the individual portions of the gastrointestinal tract.

When we built the digital representations of the equine gastrointestinal tract, we did it organ by organ, starting with the largest portions of the gastrointestinal tract, the large colon and cecum. As we added the other structures, we paid strict attention to maintaining the relative sizes of the individual organs and minor adjustments in size or shape were made as each was positioned within the shell of the horse's body. As a result, we were able to create

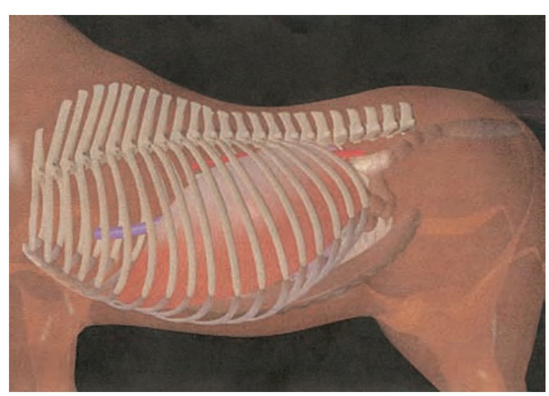

Fig. 2. Left side of the horse after removal of the skin, muscles, and ribs.

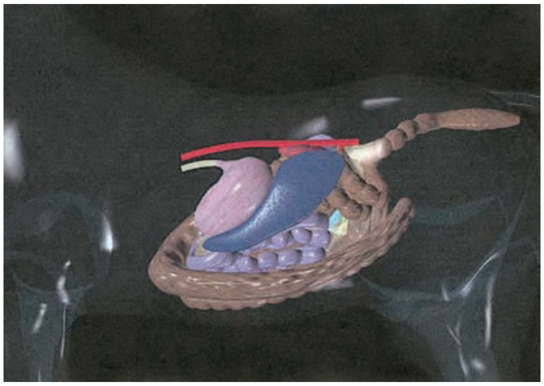

Fig. 3. Left side of the horse, after removal of the diaphragm, showing the gastrointestinal tract, spleen, liver, and kidneys.

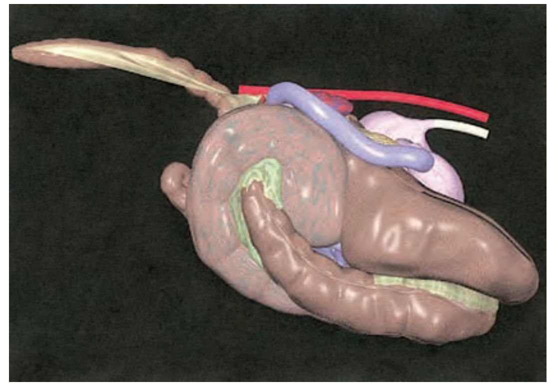

Fig. 5. Right side view depicting the cecum, right colons, right kidney, and duodenum.

and position all of the relevant portions of the gastrointestinal tract and allow them to be viewed from different vantage points.

After we created the models on our development computers, we decided to deliver our animations using a digital format known as QuickTime Movies. We chose QuickTime as our platform because it is free to the public (www.quicktime.com) and cross-platform (available for many computers, e.g., Windows, Macintosh, etc.). Using QuickTime, it was possible to isolate individual portions and provide different views of each (Figs. 3–8). A feature of QuickTime, Virtual Reality (VR), allowed us to create complex interactive images that give the viewer full control over the view he/she wishes to use to examine the gastrointestinal tract either as a unit or as individual pieces. These VR movies allow the viewer to rotate the image through 360 degrees at his/her own rate and preference.

These VR movies became more important after representations of some of the intestinal displacement were complete. They can be rotated to view relevant portions of the displacement and examine the position of the intestinal tract from either side of the horse, the ventral abdomen (to simulate the position of the intestine during colic surgery), and from the rectal view. Because of the critical importance of the rectal examination during the evaluation of horses with colic, we also paid strict attention to the rectal view of the gastrointestinal tract under normal and abnormal situations. In an effort to mimic what might be felt during the rectal examination, we created a special rectal exam view in which structures cranial to the level of the cranial mesenteric artery, and thus out of the veterinarian's reach, are obscured (Fig. 9).

Relevant Anatomic and Physiologic Principles

The stomach of the horse, which normally has a capacity of 8–16 liters, is located on the left side of the abdomen beneath the rib cage (Fig. 6). The stomach has three basic functions: storage, mixing, and breakdown of feed. Although fluid exits the stomach quickly, feed particles are retained for more than 48 hours while digestion is initiated by hydrochloric acid and periodic contractions of the muscles in the stomach wall. The peculiar anatomic arrangement between the distal esophagus and the cardia permits the movement of gas and fluid into the stomach but not out of it, thereby creating a functional one-way valve. Conse-

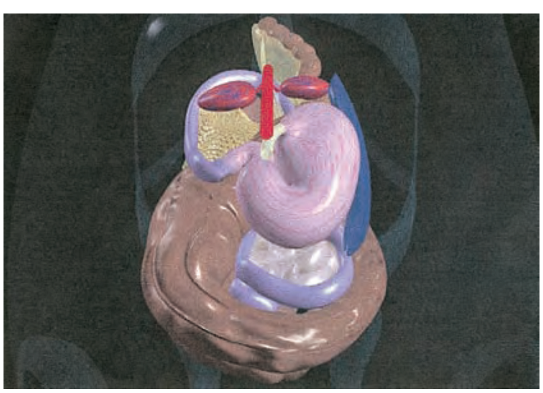

Fig. 4. Cranial view of the gastrointestinal tract.

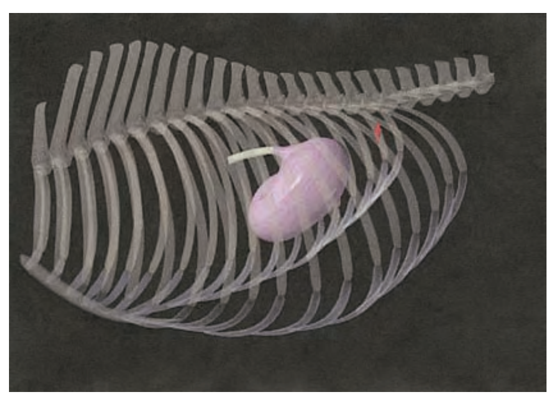

Fig. 6. Isolated view of the stomach within the rib cage; the cranial mesenteric artery is included for orientation purposes.

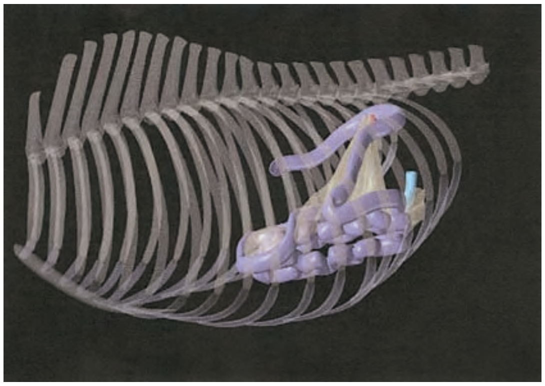

Fig. 7. View of the small intestine from the horse's left side.

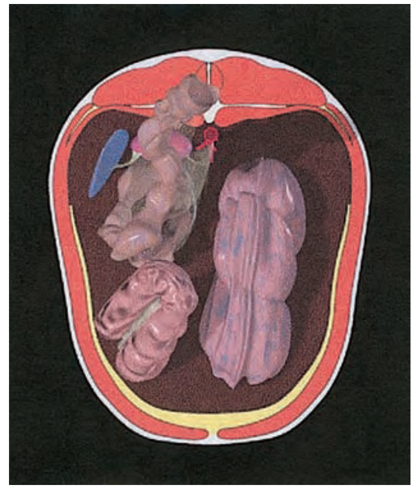

Fig. 9. Rectal exam view of a normal horse.

quently, abnormalities that interfere with the normal aboral movement of fluid through the small intestine may cause the accumulation of fluid in the stomach (gastric reflux), severe dilation, and, if untreated, gastric rupture.[3]

The small intestine is comprised of the duodenum, jejunum, and ileum (Figs. 7–8). The initial descending portion of the duodenum is positioned dorsally on the horse's right side, where it is suspended from the dorsal body wall by a short (3–5 cm) mesentery. Pancreatic enzymes and bile are added to ingesta in the proximal portion of the duodenum. The short mesentery precludes the duodenum from being involved in small intestinal displacements that involve twisting of the intestine on its mesentery (volvulus). In the right paralumbar fossa region, the duodenum turns toward the horse's midline and passes across the dorsal aspect of the base of the cecum. It is at this point in the abdomen that the duodenum can be felt upon rectal examination if it is distended with gas or fluid, as occurs in horses with proximal enteritis.

As it crosses the dorsal midline, the duodenum changes course as the ascending duodenum. The mesentery then lengthens at the origin of the jejunum and it is this characteristic long mesentery that permits loops of the jejunum to rest on the dorsal surface of the cecum and the large colon, which rest on the ventral portion of the abdomen. The jejunum is approximately 20 m long and its length, coupled with its long mesentery, allow it to be involved in volvulus and incarcerations of the small intestine. At the termination of the jejunum, the wall of the intestine becomes muscular, the lumen narrows, and an antimesenteric mesentery originates (Fig. 7). The terminal 45 cm of the small intestine, the ileum, joins the cecum at its dorsal medial aspect, the junction being the attachment of the antimesenteric ileal mesentery to the dorsal cecal band. This ileocecal ligament is used as a landmark to locate the ileum during surgery.

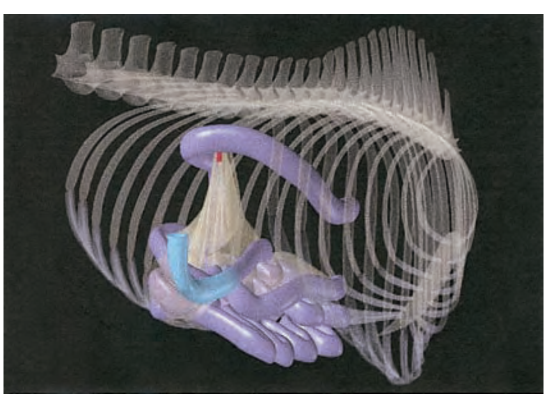

Fig. 8. View of the small intestine from the horse's right side.

The cecum is a large, blind-ended fermentation vat situated primarily on the horse's right side, extending from the paralumbar fossa region to the xyphoid cartilage on the ventral midline (Fig. 5). The cecum is 1.5–2 m in length and holds approximately 30 l of feed and fluid. Contraction of the cecal musculature results in a coordinated mixing of ingesta with the microorganisms that digest cellulose.

After the digestive processes in the cecum alter the consistency and makeup of ingesta, it passes through the ceco-colic opening into the first portion of the large colon (Fig. 5), the right ventral colon. The right ventral colon is situated on the ventral aspect of the abdomen from the flank region to the rib cage. This portion of the colon has a diameter of approximately 25–30 cm and is divided by haustra into sacculations, which help mix and retain plant fibers until they are more fully digested. As the result of aboral muscular contractions, ingesta moves toward the horse's left side through the sternal flexure of the ventral colon and then into the left ventral colon. Inside the left ventral colon, which also is large and sacculated, ingesta passes caudally toward the horse's left flank area. Near the pelvic region, the diameter of the colon decreases

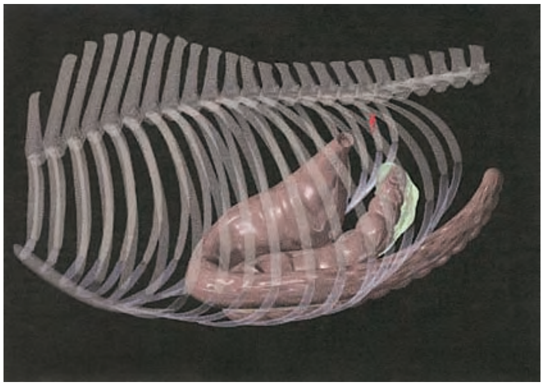

Fig. 10. Isolated view of the large colon from the horse's left side.

markedly and the colon folds back on itself. This region, which is called the pelvic flexure, is the initial portion of the unsacculated left dorsal colon (Fig. 10).

Presumably because of the abrupt decrease in diameter, the junction between the left ventral colon and the pelvic flexure is the most common location for impactions. Results of intestinal motility studies involving this region of the horse's colon provide additional information regarding the development of pelvic flexure impactions. Normograde peristaltic contractions in the left ventral colon move ingesta aborally toward the left dorsal colon; similar contractions in the wall of the left dorsal colon move ingesta toward the diaphragmatic flexure. In contrast, retrograde contractions of the muscles of the left ventral colon move ingesta in a retrograde fashion from the pelvic flexure region toward the sternal flexure. It has been hypothesized that a pacemaker region in the pelvic flexure senses either the size or the consistency of feed particles in the ingesta and then initiates the appropriate motility pattern. If digestion has proceeded sufficiently, ingesta is moved in a normograde direction. If, however, additional digestion is necessary, muscular activity occurs in a retrograde direction to retain the ingesta in the ventral colon. This hypothesis has been proposed to account for the common clinical occurrence of obstruction at or near the junction of the left ventral colon and the pelvic flexure.[4]

Ingesta then moves toward the horse's right side through the diaphragmatic flexure and into the right dorsal colon (Fig. 5). The diameters of these portions of the colon are large, with that of the right dorsal colon reaching 30–35 cm. There are no sacculations in these portions of the dorsal colon and the right dorsal colon is closely attached to the right ventral colon by a short fibrous mesentery and to the dorsal body wall by a tough common mesenteric attachment with the base of the cecum. In contrast, neither the left ventral nor the left dorsal colons are attached directly to the body wall, which allows these portions of the colon to become displaced or twisted.

Ingesta in the right dorsal colon then moves into the short transverse colon, which has a diameter of approximately 10 cm and is situated cranial to the cranial mesenteric artery. The transverse colon is fixed firmly to the most dorsal aspect of the abdominal cavity by a strong, short, fibrous mesentery. Finally, ingesta enters the sacculated descending colon, which is 4–5 m in length and has a diameter of approximately 10 cm.

Although it is important for veterinarians to be able to visualize the anatomic features and topographical layout of the horse's digestive tract, it is equally important for them to have a basic concept regarding the movement of water into and out of the various portions of the tract. An understanding of the movement of fluid within the digestive tract allows veterinarians to better appreciate the fluid needs of horses with particular intestinal abnormalities. To assist them in this understanding, we developed simple 2-dimensional animations depicting these processes. For these 2D animations we chose to use Macromedia Director because it is also cross-platform and readily animates these simple structures. Using a simple straight tube to represent the horse's gastrointestinal tract, we depicted the normal daily secretion of more than 120 l of fluid into the stomach and small intestine by the salivary glands, pancreas, and liver; reabsorption of approximately 30% of this volume by the small intestine; and reabsorption of up to 95% of the total fluid volume by the cecum, large colon, and descending colon (Fig. 11). Using this same approach, we then simulated the markedly different effects that obstruction by intestinal strangulation at the level of the mid-jejunum or by impaction at the pelvic flexure region would have on the horse's fluid status. These simple animations were developed to help explain why horses with small intestinal obstructions develop gastric reflux (Fig. 12) and need extremely large volumes of intravenous fluids whereas horses with intestinal obstructions near the pelvic flexure typically require smaller amounts of intravenous fluids.

Selected Intestinal Abnormalities

When we started to develop 3-dimensional representations of the horse's gastrointestinal tract, one of our goals was to facilitate veterinarians' under-

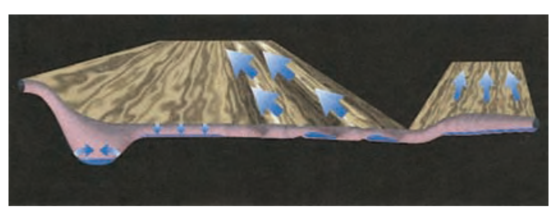

Fig. 11. Simplified representation of the horse's gastrointestinal tract showing movement of fluid into stomach/small intestine and reabsorption of fluid by small intestine, cecum, and colon.

Fig. 12. Development of gastric reflux caused by a strangulation obstruction of the small intestine.

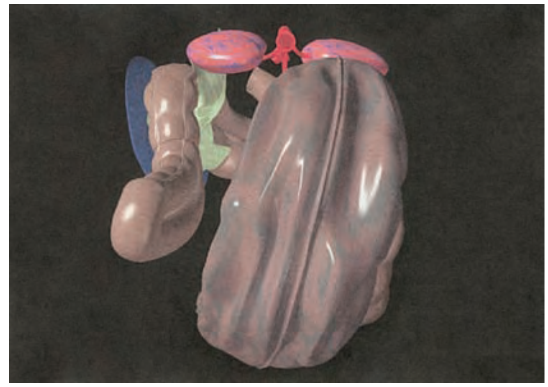

Fig. 14. Rectal examination view of a left dorsal displacement of the colon.

standing of some of the more complex or difficult-to-envision intestinal displacements. In this regard, we were most interested in producing animations depicting three commonly encountered displacements of the large colon (left dorsal displacement, right displacement, and large colon volvulus) and an abnormality affecting the small intestine that would result in distension of the small intestine that would be evident upon rectal examination. To provide the scaffolding upon which to build these more complex conditions, we initially developed a simple animation of a pelvic flexure impaction.

Left Dorsal Displacement of the Large Colon

Left dorsal displacement of the colon occurs either when the pelvic flexure or the entire left colon moves over the renosplenic ligament.[5–7] Because the renosplenic ligament does not attach to the most dorsal aspect of the spleen, a natural cleft exists between the spleen and left kidney. It has been hypothesized that the colon distends with gas, the spleen contracts as part of the response to abdominal pain, the colon then moves dorsally over the renosplenic ligament, and the spleen then refills, "trapping" the colon. We used this hypothesized route to develop the animation, concentrating on dorsolateral movement of the colon and medial displacement of the spleen because the weight of the colon is borne by the renosplenic ligament (Fig. 13). There are several findings upon rectal examination indicative of left dorsal displacement. These include palpating the pelvic flexure over the ligament, palpating the bands of the left ventral colon running dorsocranially toward the left kidney, or detecting that the spleen is displaced toward the middle of the abdomen (Fig. 14).

Pelvic Flexure Impaction

Although one of the most common sites of impaction is the pelvic flexure region of the left colon, impacted ingesta usually is not restricted to the pelvic flexure itself. In fact, it is not uncommon for the entire left ventral colon to become obstructed with dry, impacted ingesta.[4,8,9] Because the common name of the condition suggests the more restricted location for impacted ingesta, we thought it would be prudent to develop an animation depicting initiation of impaction at the pelvic flexure, with subsequent expansion to involve the majority of the left ventral colon (Fig. 15). Because the diagnosis is made upon rectal examination, we focused on producing a realistic visual representation of what can be palpated. The impacted mass may be felt to be extended cranially in the abdomen and the affected segment of

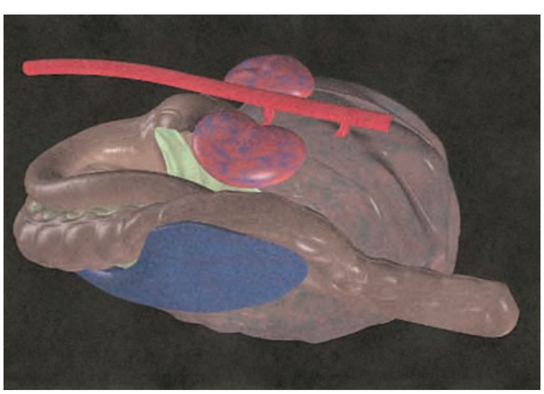

Fig. 13. Left-dorsal displacement of the colon viewed dorsally from the horse's left side.

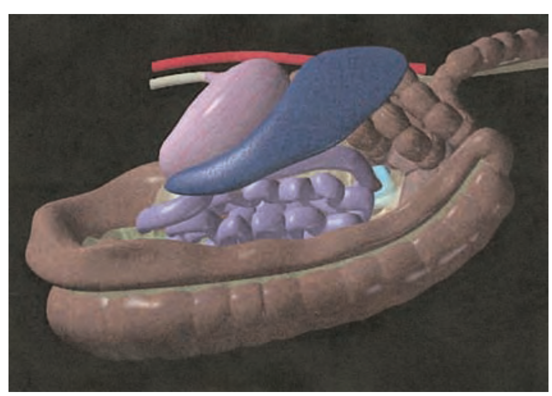

Fig. 15. Impaction of the large colon viewed from the horse's left side.

 Close window to return to IVIS

Fig. 16. Right displacement of the colon depicted from the rectal view.

Fig. 17. Volvulus of the large colon viewed from the cranial aspect of the abdominal cavity.

bowel may be identified by palpating the longitudinal bands on the surface of the ventral colon.

Right Dorsal Displacement

In this common colonic displacement, the left colons move laterally around the base of the cecum to lie between the cecum and the right body wall. There are at least two possible routes by which this displacement can develop. In one hypothesized route, the pelvic flexure moves cranially around the cecal base, caudally to the pelvic region, and then medially and cranially to lie near the diaphragm. In the process of developing this displacement, the colons twist on their longitudinal axes near the base of the cecum. In the other route, the colon becomes distended with gas and the most cranial aspects of the ventral and dorsal colons move caudoventrally and then rotate on their long axes. This results in the pelvic flexure resting near the diaphragm. Regardless of the path the colon actually takes, rectal examination findings are the same: the taenia of the colon run transversely across the pelvic inlet and difficulty is encountered when an attempt is made to palpate the ventral cecal band (Fig. 16). Although there may be some interference from venous drainage from the affected colon, the arterial supply usually remains intact and the prognosis associated with this disease is therefore quite good. Although the animation depicting the movement of the colon around the cecum seems to help veterinarians understand how this displacement occurs, more informative views are available in the QuickTime VR movie. This allows the viewer to rotate the image of the final displaced colon, thereby providing a view of the condition from any point of view.

Large Colon Torsion/Volvulus

Large colon volvulus is the most life-threatening displacement affecting the horse's large colon.[10,11] Although the term "torsion" has been used for years to indicate that the colon has twisted upon itself, the involvement of the mesentery between the ventral and dorsal colons dictates that the condition should be called a "volvulus." Because the twist occurs at the level of the cecocolic ligament and, therefore, is out of reach upon rectal examination, some veterinarians have difficulty envisioning how this condition develops and what might be palpated on rectal examination. For these reasons, we produced animations that view the condition from the cranial aspect of the abdomen, where the twisting of the colons is readily apparent (Fig. 17), as well as from the rectal view, to depict what might be palpated during a rectal examination. If the volvulus is less than 270 degrees, the bowel might be obstructed but not ischemic. If the volvulus is 360 degrees or greater, strangulation obstruction of the entire left colon occurs. As was mentioned for right displacement, the QuickTime VR movie allows the viewer to rotate the image to view the volvulus from the surgical point of view (Fig. 18).

Small Intestinal Strangulation Obstruction

Based primarily on the fact that conditions affecting the small intestine are less prevalent, some newly graduated veterinarians encounter difficulty in identifying a distended small intestine in horses with colic. Consequently, these veterinarians tend

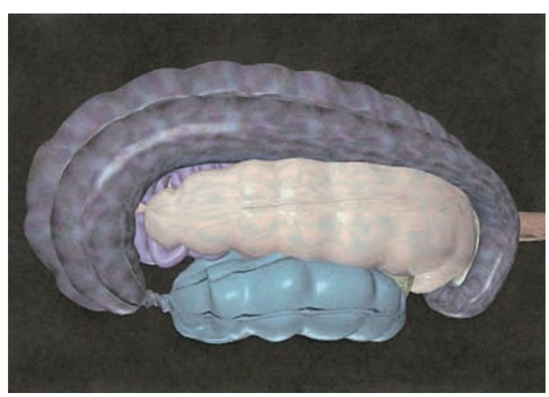

Fig. 18. Volvulus of the large colon from the ventral abdominal point of view.

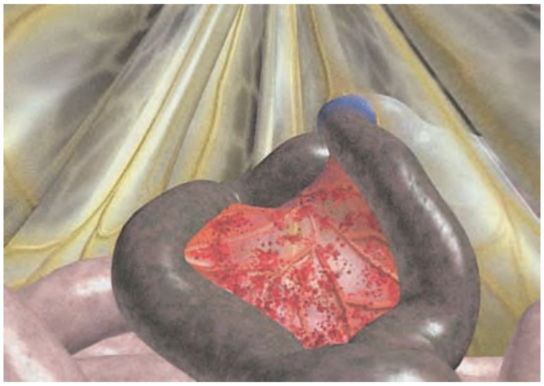

Fig. 19. Incarceration of the small intestine through a mesenteric rent.

to have difficulty envisioning how the affected small intestine is positioned in the caudal aspect of the abdomen and how incarcerations through mesenteric rents or the epiploic foramen might occur.[12,13] Although we contemplated creating an animation of an epiploic foramen entrapment, we decided that a more rational approach would be to develop a more straightforward incarceration of distal jejunum–proximal ileum through a mesenteric rent. The resulting animation depicts movement of the intestine through the rent, thickening of the intestinal wall caused by impairment of venous drainage, obstruction of the intestinal lumen and blood supply, and distention of the jejunum proximal to the obstruction (Fig. 19).

Conclusion

Based on responses we have received from veterinarians at continuing education seminars and from veterinary students in our courses, there appears to be a place for 2- and 3-dimensional images/animations in teaching basic topographical anatomy and explaining how certain intestinal displacements might develop. It is important to recognize that computer-generated images and animations, whether they are created in two or three dimensions, cannot replace true-life experiences.Although these images augment information gleaned from manipulating the horse's gastrointestinal tract in the anatomy laboratory or on the postmortem floor, they do not replace hands-on experiences or the time and effort required to become proficient in performing a thorough rectal examination. Even so, these images are based on solid educational practice, they provide veterinarians and veterinary students with the framework necessary to master difficult concepts, and they provide information in a format that can be controlled by the user for optimal understanding.

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[a]SiliconGraphics, 1600 Ampitheatre Pkwy, Mountain View, CA 94043.

[b]Alias/Wavefront, 210 King Street East, Toronto M5AIJ7, Canada.