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Szarka LA, Camilleri M. Methods for measurement of gastric motility. *Am J Physiol Gastrointest Liver Physiol* 296: G461–G475, 2009. First published January 15, 2009; doi:10.1152/ajpgi.90467.2008.—There is an array of tests available to measure gastric motility. Some tests measure end points, such as gastric emptying, that result from several different functions, whereas other tests are more specific and test only a single parameter, such as contractility. This article reviews the tests most commonly available in practice and research to evaluate in vivo the gastric functions of emptying, accommodation, contractility, and myoelectrical activity. The rationale for testing, the relative strengths and weaknesses of each test, and technical details are summarized. We also briefly indicate the applications and validations of the tests for use in experimental animal studies.

contractility; emptying; accommodation; gastroparesis; dyspepsia

ASSESSMENT OF THE MOTOR FUNCTIONS (motility) of the stomach is important in studies of gastric physiology and pathophysiology. Although not generally applied in gastroenterological practice, there is increasing use of tests to evaluate gastric function, particularly less invasive tests in clinical settings.

There is an array of tests available to measure gastric motility. Some tests measure end points, such as gastric emptying, that result from several different functions, whereas other tests are more specific and test only a single parameter, such as contractility. This article reviews the tests most commonly available in practice and research to evaluate in vivo the gastric functions of emptying, accommodation, contractility, and myoelectrical activity. The rationale for testing, the relative strengths and weaknesses of each test, and technical details are summarized. A brief discussion is also provided for methods that have been used in animals to study motor functions of the stomach in animals.

Tests to Evaluate Gastric Emptying of Solids

Gastric emptying is a composite end point reflecting a variety of functions including gastric accommodation, the pressure gradient between the proximal and distal stomach, and antropyloroduodenal contractility and coordination. The trituration of solids and emptying of solid and liquid food from the stomach are arguably the most important physiological functions of the stomach. Abnormal gastric emptying, either accelerated at 1 h or delayed at 4 h, is among the factors that contribute to reporting of dyspepsia or the development of postprandial symptoms after meal challenge (35). For all tests of gastric motility and emptying, there are standard precautions (1): *1*) Drugs affecting gastric motility (e.g., anticholinergics, narcotics, and prokinetics) are stopped for 48 h prior to the test, and the study is performed in the morning after an overnight fast. *2*) Diabetic subjects should have a glucose level <275 mg/dl. *3*) At the time the meal is ingested, Type 1 diabetic patients should receive half of their normal insulin dose.

Gastric Emptying Scintigraphy

Gamma camera scintigraphy is the most widely used test for the assessment of gastric motility; nuclear medicine facilities are generally available at community radiology centers. Scintigraphy is regarded as the gold standard because it provides a direct, noninvasive quantification of gastric emptying (5, 15). However, the clinical use of gastric emptying by scintigraphy has been hampered by lack of standardization with regard to meal composition, patient positioning, timing of image acquisition, and lack of appropriate normal values with some of the meals used. Additionally, scintigraphic imaging involves radiation exposure, requires costly gamma camera equipment, and is time intensive for patients and medical personnel. A simplified imaging protocol to obtain images at 1, 2, and 4 h with a standard meal was first proposed at Mayo Clinic (16), and a variation using a commercial and standardized meal was subsequently validated in a large multinational study in 123 subjects (129). The standardized meal and study protocol have been recommended for adoption across institutions by a consensus statement from the American Neurogastroenterology and Motility Society and the Society of Nuclear Medicine (1).

Method. The standard meal for scintigraphic gastric emptying consists of 4 ounces of Eggbeaters or equivalent egg white substitute, 2 slices of bread (120 kcal), strawberry jam (30 g, 74 kcal), and water (120 ml) radiolabeled with 0.5–1 mCi ^{99m}Tc sulfur colloid. The egg white, to which the ^{99m}Tc is added, is cooked, either scrambled in a nonstick frying pan or microwaved in an appropriately shielded container. The subject ingests the whole sandwich meal and water within 10 min.

Gamma camera images are acquired using a 140 keV photopeak with a 20% window (140 keV $\pm$ 10%), which is optimal for detection of gamma radiation from the ^{99}Tc. A low-energy all-purpose collimator maximizes the count rate; a low-energy high-resolution collimator can also be used. Computerized digital images acquired in a 128 $\times$ 128 word mode matrix are required for quantification.

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Images are obtained immediately after meal ingestion and at 1, 2, and 4 h after the meal with the subject standing upright in front of a gamma camera. If a single-headed camera is used, the subject is first imaged anteriorly for 1 min and then immediately asked to stand with his or her back to the camera for the 1-min posterior image. These may be acquired simultaneously if a dual-headed camera is available. For patients who cannot stand or be positioned for anterior and posterior views, a single best left anterior oblique (LAO) image may be substituted. In between imaging sessions, subjects are permitted to sit or walk to and from the imaging room and bathroom as desired. Strenuous activity should be avoided.

Image analysis and quantification of gastric emptying is performed by manually drawing regions of interest (ROI) on the anterior and posterior images for all acquisition times by using an irregular ROI program to outline the stomach. A first image, immediately after meal ingestion, uses an ROI that encompasses all the radioactivity in the abdomen, to estimate 100% radioactivity at *time t* = 0. The gastric ROI should include the fundus and antrum with particular attention to avoid any loops of small bowel in close proximity to the stomach. The geometric means of the anterior and posterior gastric counts [(anterior counts × posterior counts)$^{1/2}$] for each time point are calculated to account for tissue attenuation and corrected for ^{99m}Tc decay (half-life 6.02 h). No correction for tissue attenuation is required for the LAO images.

Indications. 1) Unexplained nausea, vomiting, and dyspeptic symptoms; *2*) assessment of gastric motility prior to fundoplication; *3*) assessment of gastric motility prior to small bowel transplantation or colectomy for colonic inertia; *4*) screening for impaired gastric emptying in diabetic patients being considered for treatment with medications that may further retard gastric emptying (e.g., pramlintide and GLP-1 agonists); *5*) assessment of patients with suspected diffuse gastrointestinal (GI) motility disorder, by combining gastric emptying with small bowel and colonic transit.

Contraindications. Healthy children and pregnant women, due to radiation exposure.

Interpretation. The final results are expressed as percent remaining in the stomach at each time point with the total gastric counts normalized to 100% for the *time t* = 0 (first image immediately after meal ingestion). The percent remaining in the stomach at each time point is reported (Fig. 1). The normal values (129) at the key time points are 1 h (37–90%), 2 h (30–60%), and 4 h (0–10%). Delayed gastric emptying is usually diagnosed when there is >10% retention at 4 h or more than 40% retained at 2 h. However, there are instances when gastric emptying may be initially slow with >40% retained at 2 h but <10% retained at 4 h. Such patients may still benefit from treatment intended to increase gastric emptying during the first 2 postprandial hours.

Accelerated emptying is less easily identified by using this standard meal given the wide range (up to 90% emptied) observed in health with this low-calorie and low-fat, easily digested meal. However, many centers use a cutoff of >70% emptied in the first hour as indicative of accelerated gastric emptying. Identifying accelerated gastric emptying may therefore require use of higher calorie meal (16) or nutrient liquids as the radiolabeled substrate. It is also worth noting that some patients may have delayed gastric emptying at 1 and 2 h, but normal emptying by 4 h. Such patients may benefit from prokinetic therapy.

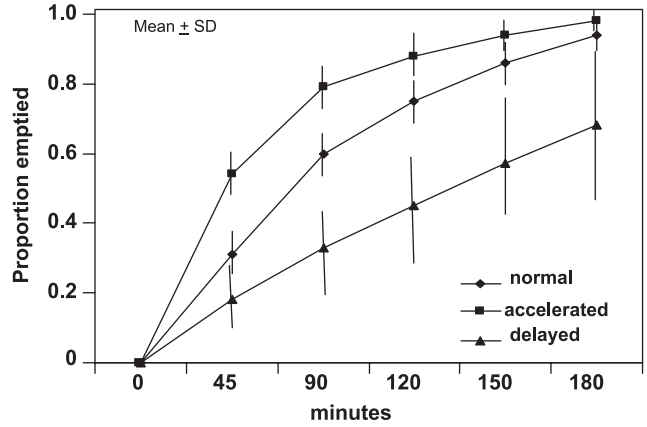

Fig. 1. Summary of scintigraphic gastric emptying results by $t_{1/2}$ group in 129 subjects with clinically suspected delayed gastric emptying. Data show means ± SD. Reprinted from Szarka LA, Camilleri M, Vella A, Burton D, Baxter K, Simonson J, Zinsmeister AR. A stable isotope breath test with a standard meal for abnormal gastric emptying of solids in the clinic and in research. *Clin Gastroenterol Hepatol* 6: 635–643, 2008, with permission from Elsevier.

Pitfalls. The most pervasive pitfall in gastric emptying by scintigraphy is the use of short-duration detailed studies, lasting <2 h, and extrapolating the $t_{1/2}$ or the proportion emptied at 4 h using a power exponential analysis. This pitfall often leads to erroneous assumptions about the real gastric emptying at 4 h. This pitfall was the basis for the initial emphasis of obtaining images at 3 and 4 h (16) and should no longer be an issue if the consensus guideline on scintigraphic gastric emptying is adopted by all centers (1).

There is significant intraindividual variation in gastric emptying rates of 12–15%, even in healthy individuals (25, 34). The relationship of gastric emptying rates of the 200-kcal meal to symptoms remains controversial (122). Alterations in gastric emptying and reduced gastric volumes during fasting and postprandially account for <50% of the variance in the symptoms after a challenge meal (35). The degree of delay on the scintigraphy study is only one factor that determines the severity of gastroparesis, which is better assessed by a combination of clinical parameters such as frequency of vomiting, state of hydration and nutrition, and ability to sustain nutritional status orally, as well as the gastric emptying rate (14).

Validation and application of method to small animals for research. There is a vast literature on the use of radioscintigraphy to measure gastric emptying in large animals. The first study to apply radioscintigraphy used ^{198}Au-colloid to document the effects of vagotomy and carbachol on gastric emptying in dogs (128). The method was attributed to a surgeon, Mr. H. Daintree Johnson FRCS, who developed the method in 1969.

More recently, gamma camera scintigraphy has been validated for use in small animals. Thus awake mice were accustomed to light restraint and to feeding cooked, egg white (0.00 g fat), whole egg (0.10 g fat/g), or egg yolk (0.31 g fat/g). Gastric emptying of each diet was measured by labeling the test meals with ^{99m}Tc-mebrofenin and using a conventional gamma camera equipped with a high-resolution, parallel-hole collimator. Gastric emptying of cooked whole egg was also

determined following administration of either vehicle or the CCK A receptor antagonist devazepide. The $t_{1/2}$ was significantly increased with increasing triglyceride content. Administration of devazepide (CCK A receptor antagonist) significantly accelerated gastric emptying of whole egg (136). The effect of botulinum toxin injection into the antral wall was shown to accelerate gastric emptying by scintigraphy (28).

Similarly, the literature demonstrates the power of small animal scintigraphy to document biological effects in knockouts as well as pharmacological modulation (137, 138).

Another application of the method has been used to examine the role of inflammation and novel therapies for postoperative ileus in animal models (124, 125).

Wireless pH and Motility Capsules

Nondigestible wireless capsules can measure pH, pressure, and temperature throughout the GI tract. The abrupt change in pH from the acidic gastric milieu to the almost alkaline duodenum is usually associated with antral phasic contractions at the maximal frequency of the migrating motor complex (MMC), and it signals that the capsule has left the stomach (75). When taken with a meal, the capsule generally empties from the stomach after liquids and triturable solids have emptied, and this occurs with the return of the phase III of the MMC or, in about one-third of cases, this occurs with high-amplitude, isolated antral contractions (17).

Method. In initial studies, patients ingested the capsule with 50 ml of water and began eating the standard meal (as used in the scintigraphy method but without the radioisotope) with an additional 120 ml of water. In more recent studies, the meal is administered first, followed by the wireless pH and motility capsule. Subjects are ambulatory but are encouraged to sit. Six hours after capsule ingestion, patients can engage in normal daily activity, including ad libitum feeding. The wireless capsule acquires data continuously for up to 5 days, and this permits calculation of small bowel, colon, and whole gut transit. An "event button" is used to mark significant events (such as meal ingestion, sleep, or GI symptoms experienced by the patient). To standardize test conditions and facilitate interpretation, there should be no strenuous activities such as sit-ups, abdominal crunches, or prolonged aerobic activity (>15 min). At 72 h postingestion, subjects return with the data receiver. Capsule exit can be confirmed by abdominal X-ray in subjects with GI motility disorders unless the subject observes passage of the capsule. When the data from the recorder are downloaded to a personal computer, specialized software (e.g., SmartPill MotiliGI used in conjunction with the commercially available SmartPill) generates a summary report of the computed gastric emptying time (in minutes), small/large bowel transit time, whole gut transit time, and high/low gastric pH values. The latter may be useful to identify previously unsuspected gastric hypochlorhydria, which may result from atrophic gastritis or vagal dysfunction. These wireless capsules also measure intraluminal pressure, and further validation studies of the significance of these measurements are the subject of ongoing research.

Indication. Suspected delayed gastric emptying.

Contraindications. History of gastric bezoar, dysphagia, suspected strictures, fistulae, or active pseudo-obstruction, GI surgery within the last 3 mo, Crohn's disease, known small bowel diverticulosis, extensive or complicated colonic diverticulosis, and subjects who use implanted or portable electromechanical medical devices such as cardiac pacemaker or infusion pump. The wireless capsule motility study is not intended for use in pediatric patients.

Performance. In validation studies conducted with simultaneous gastric emptying scintigraphy in healthy subjects and patients with gastroparesis, the gastric emptying time obtained with a wireless pH and motility capsule, and the scintigraphic gastric emptying time at 4 h were significantly correlated [$r = 0.73$ (74)]. In general, an abnormal gastric emptying of the capsule is defined by gastric retention of >5 h. Wireless motility capsules cannot provide dynamic information regarding the emptying of a digestible meal since they are nondigestible, larger than the 1- to 2-mm size of triturated digestible food emptied from the mammalian stomach, and signal only the capsule emptying time (88). However, the capsule discriminates between normal or delayed gastric emptying with a sensitivity of 0.87 at a specificity of 0.92 (74). The advantages of the motility capsule are ease of conduct of the study anywhere, reasonable discrimination between normal and delayed gastric emptying, lack of radioactivity, and ability to determine small bowel, colon, and whole gut transit times, as well as gastric contractility (103, 104). The only safety issue is the possibility of capsule retention.

Pitfalls. The wireless motility capsule does not measure the emptying of digestible food, but rather the emptying of indigestible solids most commonly with phase III of the MMC. Some healthy subjects have as few as one phase III during a 24-h period (83); hence, the emptying of the motility capsule may vary widely. A gastric emptying time of 6 h is assigned if the capsule does not record pH >6 over the first 6 h. Conversely, stationary antroduodenal manometry studies show that a number of subjects have a phase III activity front induced within 5 min of onset of eating a solid-liquid meal. This could potentially cause the capsule to empty before the digestible solids are triturated. The capsule may also empty with isolated antral contractions unrelated to the antral phase III activity front (117). Hence the time of capsule emptying does not always reflect the time of return of fasting motility, which may be a surrogate for the end of gastric emptying of the meal.

The wireless capsule does not provide information about the dynamics of gastric emptying, such as the pattern of gastric emptying in the early postprandial period, which may also contribute to dyspeptic symptoms (1). In patients with severe gastroparesis who have difficulty emptying indigestible solids and who are predisposed to formation of gastric bezoars, the capsule may not empty at all. Finally, it should be emphasized that there are still no reports demonstrating clinical utility or documenting correlation with symptoms for the wireless pH and motility capsule.

Stable Isotope Breath Tests

These tests constitute a promising method to evaluate gastric emptying noninvasively and without radiation hazard. ^{13}C isotope can be incorporated into a solid meal, either through incorporating ^{13}C into the synthesis of the medium-chain fatty acid octanoic acid or by growing the blue-green algae *Spirulina*

platensis in $^{13}CO_2$-enriched chambers. [^{13}C]acetate can also be included in a liquid meal to assess gastric emptying of liquids. If there is to be combined assessment of emptying of solids and liquids, one phase of the meal can be labeled with ^{14}C and the other with ^{13}C.

After ingestion, the solid meal is triturated and emptied by the stomach, digested (*S. platensis* only), and absorbed in the proximal small intestine, metabolized by the liver and excreted by the lungs, resulting in a rise in expired $^{13}CO_2$ over baseline. The test and breath sample collection can occur at any location. This test assumes that the rate limiting step in $^{13}CO_2$ excretion is gastric emptying of the labeled test meal.

Method. The methods used by all laboratories are adapted from the original, pioneering work of Ghoos and colleagues (51, 82). There is no commercially available standard meal at the time of this publication. The method described below is an example from a recent validation study (120).

The test meal used contained 100 mg ^{13}C-*S. platensis*, 27 g freeze-dried egg mix, 6 saltine crackers, and 180 ml of water (120), with caloric content of 238 kcal and a balanced composition (16.9 g carbohydrates, 14.4 g protein, and 11.2 g fat). End-tidal breath samples were collected at baseline (before the test meal) and 45, 150, 180 min after ingestion of the test meal. Breath samples were stored in glass screw-cap Exetainer tubes (Labco, High Wycombe, UK) by using a straw to blow into the bottom of the tube to displace contained air. After the tubes were recapped, the $^{13}CO_2$ breath content was determined at a centralized laboratory or by desktop isotope ratio mass spectrometry.

The ^{13}C enrichment was expressed as the delta per milliliter difference between the $^{13}CO_2$-to-$^{12}CO_2$ ratio of the sample and the limestone standard, Pee Dee Belemnite; CO_2 production was corrected for age, sex, height, and weight by using the algorithms of Schofield (106). Calculations of the $^{13}CO_2$ enrichment are described in detail elsewhere (120).

Indications. Same indications as for scintigraphy, including application in children and pregnant women.

Performance characteristics. In studies comparing ^{13}C gastric emptying breath tests (GEBT) performed simultaneously with scintigraphy, the ^{13}C GEBT provides an accurate assessment of the gastric emptying of solids with an acceptable coefficient of variation that is comparable to scintigraphy (25) and is similar with two different meal substrates [egg and biscuit (77)]. ^{13}C-*S. platensis* GEBT was able to identify accelerated or delayed gastric emptying induced pharmacologically with erythromycin or atropine (134). At present, there is no standardized meal for the breath test. We believe that, at present, the best validated meal is the shelf-stable 238-kcal meal consisting of freeze-dried egg mix labeled with ^{13}C-*S. platensis*, saltine crackers, and water. This meal was simultaneously evaluated with scintigraphy in 38 healthy volunteers and 129 patients with suspected delayed in gastric emptying. Individual breath samples at 45-, 150-, and 180-min time points correctly predicted gastric emptying category: at 80% specificity, the combined 45- and 180-min samples were 93% sensitive to identify accelerated gastric emptying, and the combined 150- and 180-min samples were 89% sensitive for identifying delayed gastric emptying [Fig. 2 (120)]. The current lack of a commercially available standard meal prevents widespread adoption of this technology for clinical use. The potential advantages of stable isotope ^{13}C GEBT include absence of radiation hazard, application in children and pregnant women, ease of administration of the test even in remote locations, and performance of test being operator independent.

Pitfalls. For the ^{13}C-based breath tests, pitfalls include potential loss of accuracy in patients with other diseases involving the intestinal mucosa, pancreas, liver, and respiratory system. [^{13}C]octanoic acid is absorbed across the mucosa undigested, so it is not dependent on biliary and pancreatic secretions or mucosal enzymes; moreover, the oxidative break-

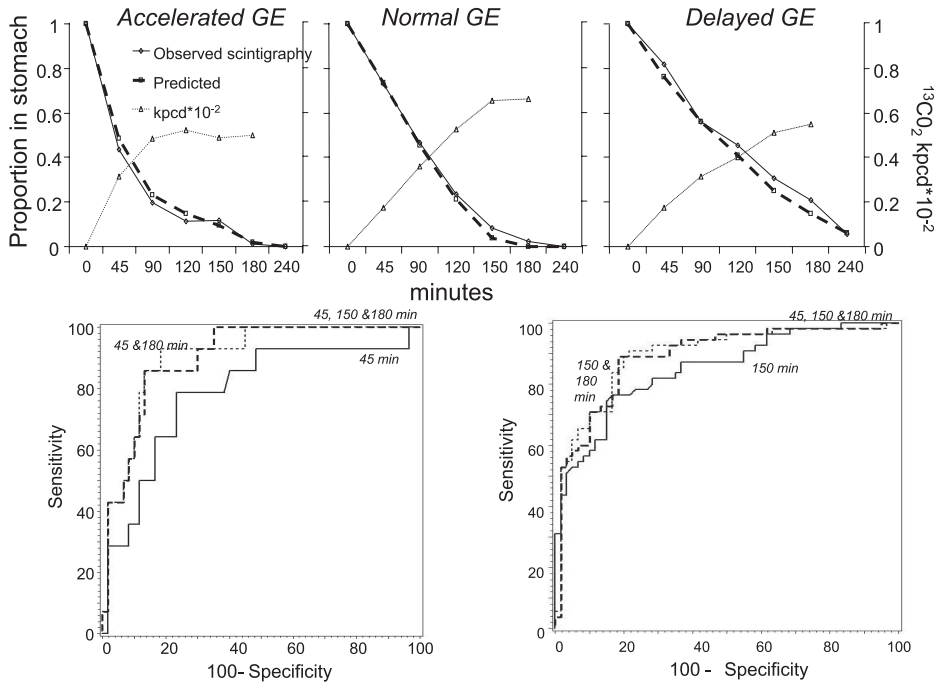

Fig. 2. *Top*: accuracy of $^{13}CO_2$ excretion to predict simultaneously measured gastric emptying (GE) of solids in examples with normal, accelerated, or delayed gastric emptying. The ability of the breath test kpcd*t* [percent dose excreted (kpcd) at *time t*] values to predict scintigraphic $t_{1/2}$ values was assessed by using a logistic regression model (with the 3-group category as the dependent variable) and the breath test kpcd values as predictors. A backward elimination approach was used to identify the best subset of kpcd values to predict the $t_{1/2}$ category of each subject. *Bottom*: receiver operating characteristic (ROC) curve for the detection of accelerated (*left*) or delayed (*right*) gastric emptying with breath test measurements relative to the simultaneous scintigraphic measurement. Reprinted from Szarka LA, Camilleri M, Vella A, Burton D, Baxter K, Simonson J, Zinsmeister AR. A stable isotope breath test with a standard meal for abnormal gastric emptying of solids in the clinic and in research. *Clin Gastroenterol Hepatol* 6: 635–643, 2008, with permission from Elsevier.

down of [^{13}C]octanoic acid appears to be unaffected in patients with advanced liver disease (105, 132). [^{13}C]octanoic acid-based GEBT may be affected by diseases reducing the absorptive capacity of the small intestine and advanced pulmonary disease. Breath excretion of $^{13}CO_2$ from either the ^{13}C-*S. Platensis* or the [^{13}C]octanoic acid GEBTs may be affected by hemodynamic changes, including vigorous physical exercise, sepsis, or hyperdynamic circulation. The optimal mathematical analysis for GEBT is the subject of controversy with different approaches and corrections recommended (51, 77, 82, 94, 120, 134). This also needs standardization before application of GEBT in clinical practice.

Validation and application of method to animals for research. The [^{13}C]octanoic acid breath test has been used and validated for measurement of gastric emptying in large animals such as ponies and horses (119, 140).

More recently, the reliability and responsiveness of a [^{13}C]octanoic acid breath test was tested in nonobese diabetic LtJ mice, a model of Type 1 diabetes. The test produced results similar to postmortem recovery of a meal. Subsequently, the test was used to compare solid gastric emptying in nonobese diabetic LtJ mice and nonobese diabetes-resistant LtJ mice and to demonstrate the expected effects of bethanechol and atropine, which respectively accelerated and slowed gastric emptying (23).

Other Technologies for Gastric Emptying

Magnetic resonance imaging of the stomach. MRI has the potential to become an overall test to measure gastric emptying, volume change, and wall motion as a surrogate of contractile activity without radiation exposure (43, 72, 73, 76, 85, 86, 111). It also has the ability to separately assess the emptying of fat and water from the stomach (73). However, to date MRI has not been validated to the same degree as scintigraphy and gastric emptying breath tests, and there is a paucity of studies in disease states or in response to different perturbations other than the effects of different nutrients or drugs such as erythromycin. Further validation is, therefore, needed; however, with novel acquisition and projection algorithms, developed for dynamic imaging for other indications such as MR angiography and the lack of radiation exposure, there is great potential for future use of MRI to measure gastric motor functions.

METHOD. Gastric emptying is measured after administration of a liquid meal containing gadolinium tetra-azacyclododecane tetra-acetic acid as a MRI marker (110). Subjects are studied in the supine position and scanned at 15-min intervals, applying a spin-echo technique with T1-weighted images. Gastric emptying and secretion are measured by defining areas of interest on each "slice," determining the volume of each slice, and calculating total volume of gastric contents by addition of the individual slice volumes (109). To evaluate gastric contraction, the diameters of the proximal and distal stomach are determined on coronal scans and recorded (Fig. 3). Detailed analysis of each individual contraction provides visual and quantitative assessment of gastric emptying and motility. Volume measurements may also facilitate measurement of the accommodation response (24, 46).

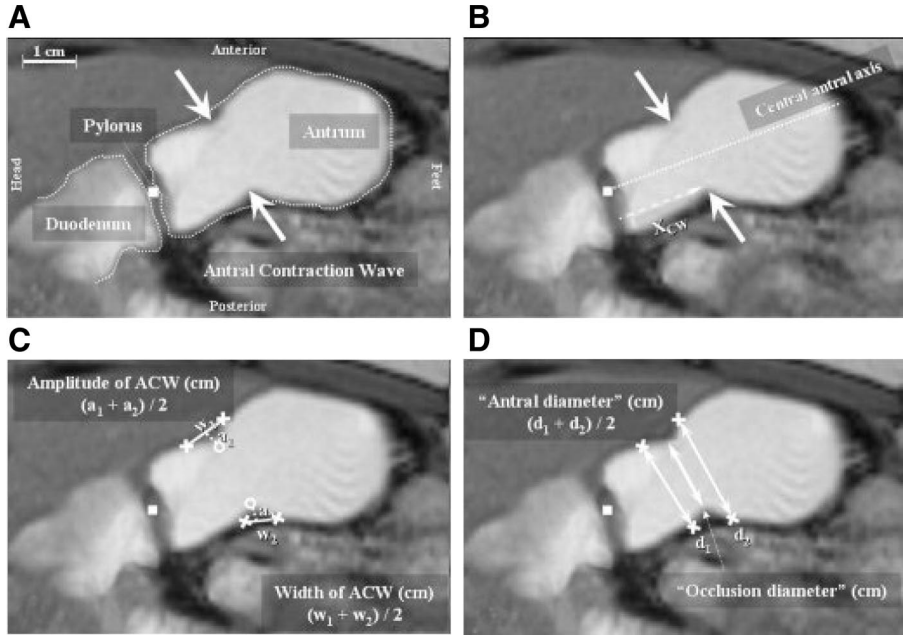

Fig. 3. Computed analysis of antral contraction waves (ACWs) as seen by MRI. Presented here is a magnification of an image through the distal antrum, pylorus, and proximal duodenum. *A*: arrows indicate the position of ACWs propagating toward the pylorus, as captured in one of 120 images of a dynamic sequence (motility scan, 167 s). *B*: long axis drawn through the center of the antrum was anchored to the indicated position of the pylorus, allowing tracking of the propagation of ACWs, as well as their position relative to the pylorus (X_{CW}, in cm). *C*: average distance (w_1 and w_2, in cm) between the bases (×) of the indentations in the antral wall, representative of ACWs, denoted the width of ACWs. The average distance (a_1 and a_2, in cm) between the tips (○) of these indentations and the w_1/w_2 denoted the amplitude of ACWs. *D*: antral diameter was measured as an average of 2 distances (d_1 and d_2, in cm) between the bases (×) of ACWs across the antrum. Similarly, the occlusion diameter was measured as a distance between the tips (○) of ACWs. Reproduced from Kwiatek MA, Steingoetter A, Pal A, Menne D, Brasseur JG, Hebbard GS, Boesiger P, Thumshirn M, Fried M, Schwizer W. Quantification of distal antral contractile motility in healthy human stomach with magnetic resonance imaging. *J Magn Reson Imaging* 24: 1101–1109, 2006. Reprinted with permission of John Wiley & Sons, Inc.

PITFALLS. Pitfalls are that MRI can only be performed in the supine position, which is a drawback since gravity is an important driving force in gastric emptying, especially of liquids (44). Subjects also need to hold their breath in expiration to reduce motion artifacts during scans. The principal drawback of MRI relates to cost and availability of equipment, imaging time, and technical expertise.

VALIDATION AND APPLICATION OF MR IMAGING IN ANIMALS. Passage of solid oral dosage forms of medications in the rat GI tract has been visualized by MR imaging (26). Gastric emptying and GI transit times in mice were monitored noninvasively by using ^{27}Al- and ^{19}F-nuclear magnetic resonance (108).

Functional ultrasonography. Functional ultrasonography can provide quantitative information about gastric motility including emptying, gastroduodenal flow, contractility, and accommodation. Real-time ultrasonography has been used to evaluate gastric emptying on the basis of the dynamic changes in the antral cross-sectional area in the axis of the superior mesenteric artery (9). Two-dimensional ultrasonography of the proximal stomach has been used to demonstrate volume changes after a meal (53) and its impairment in functional dyspepsia (55). Duplex Doppler has been applied to dynamically study transpyloric flow of liquid meals (61, 67); a short gush of duodenogastric reflux normally precedes the peristaltic closure of the pylorus; episodes of gastric emptying are defined as flow across the pylorus with a mean velocity of more than 10 cm/s, lasting >1 s (52). With this Doppler method, the timing of postprandial dyspeptic symptoms and transpyloric passage of gastric contents can be studied with great temporal and spatial resolution (59), including the effects of pharmacological intervention (58).

TRANSPYLORIC FLOW. Transpyloric flow and duodenogastric reflux stroke volumes may be quantitated by using a 3D guided digital color Doppler imaging model (60) with a 5–3 MHz phased array transducer and position and orientation of the sensor acquired by using a magnetic sensing system. There was high intra- and interindividual variations in the stroke volumes of transpyloric flow episodes during the initial gastric emptying. The duodenogastric reflux episodes lasted on average 2.4 s, with an average volume of 8.3 ml. This 3D Doppler method minimized geometric assumptions and angular ambiguity associated with 2D methods.

The advantages of ultrasonography are widely available equipment, modest running costs, absence of radiation hazard, and good interobserver agreement for the gastric emptying of a liquid meal (65). Ultrasound estimates of $t_{1/2}$ liquid emptying time (110) are closely correlated with the results with scintigraphy.

PITFALLS. Pitfalls of ultrasound include assessment of gastric emptying of liquids, which may be preserved even in advanced cases of gastroparesis. Only very few studies patients have been studied utilizing a solid meal and simultaneous scintigraphy (8, 30). Measuring gastric emptying of solids with 3D ultrasonography may be feasible but requires further validation. Other disadvantages of ultrasonography are the need for a skilled operator and suboptimal examination in people who are not lean or in the presence of air. Ultrasonography is generally impractical for prolonged observations.

VALIDATION AND APPLICATION IN ANIMALS FOR RESEARCH. There is a substantial literature demonstrating the use of ultrasonography to measure gastric volume, antropyloric contractions, and gastric emptying in large animals including dogs and calves. Recently, ultrasound has facilitated the measurement of gastric compliance (79); application of ultrasonomicrometry has been used to track coordinated gastric and pyloric motility with implantation of piezoelectric crystals affixed to the serosa in different parts of the stomach (4).

Tests to Evaluate Gastric Capacity and Accommodation

One of the principal functions of the proximal stomach is the storage of food. The gastric fundus and body are able to accommodate large volume changes while maintaining a relatively low intragastric pressure. Altered gastric tone and distensibility may occur in several disease states including gastritis, tumor infiltration, vagal dysfunction, and postgastric surgery status and in up to 40% of patients with functional dyspepsia (127).

Balloon Measurements

The gold standard for the measurement of tone in hollow organs remains the barostat (7), which estimates changes in tone by the change of volume of air in an infinitely compliant balloon maintained at a constant pressure. A variant is the tensostat (27, 42), which corrects, in real time, for the changes in volume or diameter of the balloon to estimate luminal wall tension on the basis of the Laplace law.

One measurement of gastric capacity used a latex balloon, with a capacity of ~1 liter attached to a double-lumen tube, passed orally into the stomach. A pump, placed behind the subject, was used to fill the balloon with water at a rate of 100 ml per min, with 1-min pauses to record pressure, through a second lumen. The compliance of the balloon in vitro was subtracted from the measured intragastric pressure. With each 100 ml, abdominal discomfort was rated on a 0–100 scale. The result of gastric volume was based on the maximum tolerated volume and the volume to produce a 5-cm water rise in intragastric pressure (49, 50). The second method measured gastric tone with an infinitely compliant balloon and a barostat, which imposes a constant low pressure to maintain the balloon in apposition with the stomach lining. The barostat maintains the constant pressure by infusion or aspiration of air in response to relaxation or contraction of stomach tone. Neither of these methods is used extensively in clinical practice.

Pitfalls. Pitfalls in these forms of measurement include the need for intubation and balloon distension under low constant pressure, which may result in reflex relaxation of the stomach so that a true baseline fasting volume cannot be estimated, and significant compliance of latex, which necessitates correction each time the balloon is used since the compliance may change with use as the latex is stretched by the water within the balloon. The barostat measures a volume within a balloon under constant pressure rather than true tone, volume, or tension in absolute terms. These invasive tests are often unacceptable to patients who are stressed and uncomfortable during these tests, which may last 3 h or more (130). Given the practical limitations of balloon measurements of gastric volume and accommodation, noninvasive volume-based methods have been proposed to measure gastric capacity during fasting and postprandially in the clinical setting and in research.

Validation and application in animals for research. Development and validation studies of the barostat to measure

compliance, tone, and postprandial accommodation in the dog were performed by Azpiroz and Malagelada (7). Since then, the barostat has been used extensively in large animals including cats, pigs, rabbits, opossums, and horses. More recently, it has also been used to study tension and wall stress in rats (141), gastric volume changes in response to central vagal stimulation in mice (93), and central administration of pharmacological agents in rats (102).

SPECT

Single photon emission computed tomography (SPECT) imaging has been extensively validated in vitro and in vivo for the measurement of gastric volumes during fasting and postprandially. Validation includes comparison to the "gold" standard, the barostat (10, 32, 37, 71).

Method. After intravenous administration of 10–20 mCi [^{99m}Tc]pertechnetate, which is taken up by the parietal and mucin-secreting cells of the gastric mucosa, tomographic images of the stomach are acquired with the patient supine using a large field-of-view, dual-headed gamma camera. From the transaxial images of the stomach, 3D images can be reconstructed and total gastric volume can be measured during fasting and during the first 30 min following a meal consisting of 300 ml Ensure (Ross Products, Division of Abbott Laboratories, Columbus, OH; 316 kcal, 7.6 g fat, 50.6 g carbohydrate, and 11.4 g protein). Refinement of the analysis programs has reduced analysis time from several hours to less than 2 min on average per image of stomach in the fasting or postprandial periods.

SPECT demonstrates effects of disease on postmeal change in gastric volume, a surrogate of gastric accommodation (11), and the effects of medications such as nitrates, erythromycin, GLP-1, and octreotide (36, 80) in health and in diseases such as diabetes, postfundoplication, and functional dyspepsia (38). These effects of medications are consistent with those observed with the barostat in the published literature. This noninvasive test does not require intubation and measures the volume of the entire stomach, in contrast to the barostat, which measures tone in part of the stomach. Intraobserver coefficients of variance in estimated fasting and postprandial volumes were 9 and 8%; interobserver variations were 12 and 13%, respectively (71). The effects of liquid and solid equicaloric meals on gastric volumes have been described, and measurements of gastric volume with the same caloric liquid meal an average of 9 mo apart show a coefficient of variation of ~10% (31).

A new measurement is the simultaneous measurement of gastric emptying and volume (Fig. 4), first demonstrated by Parkman's group (112). This is of significant potential research interest because it provides thorough assessment of the pathophysiology of the stomach in disease. With the method described from Temple University, gastric "accommodation" is calculated as the percent change in planar (2D) gastric cross-sectional area by using a left anterior oblique planar projection and the percentage change in total SPECT gastric voxel counts (by 3D imaging) compared with baseline fasting volume using NIH image software (http://rsb.info.nih.gov/ij/index.html). The procedure includes anterior and posterior images for estimation of gastric emptying, followed by SPECT imaging with a separate SPECT camera every 20 min. A Mayo Clinic study confirmed the ability to measure the dynamics of gastric volume and emptying functions (Fig. 5) in health using the same SPECT camera (12).

Indication. Suspected disorders of gastric accommodation, such as in dyspepsia.

Pitfalls. Radioactive isotopes are used. The SPECT equipment is not widely available, and sophisticated software is needed to perform the 3D reconstruction and volume rendering. Measurements can only be obtained in the supine position, eliminating the influence of gravity, which is a drawback shared with MRI. Gastric sensation cannot be assessed by SPECT, unlike the barostat study. The main limitation for the

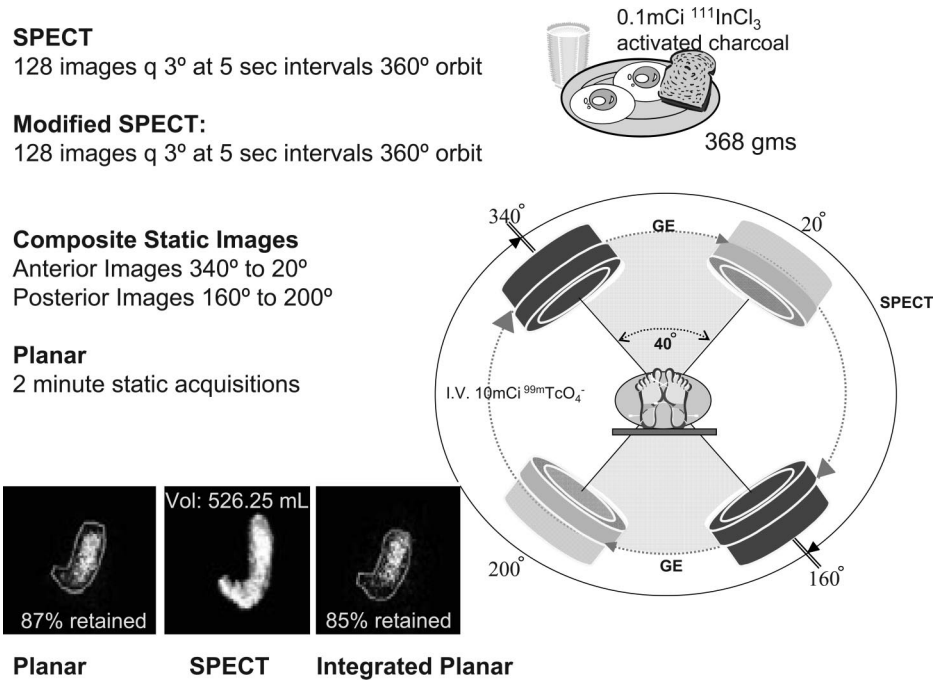

Fig. 4. *Top*: method for combined measurements of gastric volume and emptying. Adapted from Burton DD, Kim HJ, Camilleri M, Stephens DA, Mullan BP, O'Connor MK, Talley NJ. Relationship of gastric emptying and volume changes after a solid meal in humans. *Am J Physiol Gastrointest Liver Physiol* 289: G261–G266, 2005. *Bottom*: images of the stomach by planar scans, single photon emission computerized tomography (SPECT), and composite SPECT acquisition to construct anterior image. Note that the amount of food retained in the stomach is similar when calculated using the traditional 2D or planar anterior and posterior gamma camera images and the integrated images obtained using the method outlined above using a 3D acquisition. The central image demonstrates the stomach volume simultaneously estimated using SPECT. Reproduced from Camilleri M. New imaging in neurogastroenterology: an overview. *Neurogastroenterol Motil* 18: 805–812, 2006.

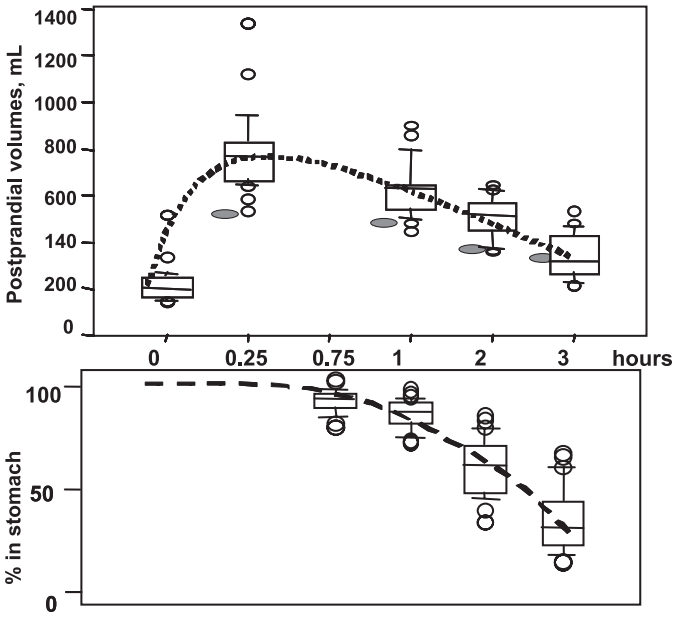

Fig. 5. Time course of simultaneously acquired postprandial gastric volume and gastric emptying using SPECT imaging. Reproduced from Burton DD, Kim HJ, Camilleri M, Stephens DA, Mullan BP, O'Connor MK, Talley NJ. Relationship of gastric emptying and volume changes after a solid meal in humans. *Am J Physiol Gastrointest Liver Physiol* 289: G261–G266, 2005.

evaluation of accommodation by SPECT is the lack of effective treatment for identified abnormalities.

Satiation or Nutrient Drink Test

The nutrient drink test has been proposed as a surrogate method for estimating gastric volumes. In this test, a standardized liquid nutrient drink, such as Ensure (1 kcal/ml, 11% fat, 73% carbohydrate, and 16% protein), is ingested at a standard rate of 30 ml per min, and the maximum tolerated volume, used as a measure of satiation by the symptoms of nausea, bloating, and pain, can also be measured 30 min after the meal (21). Tack et al. (121) suggested that a high-caloric, slowly administered drinking test compared favorably with the barostat in predicting impaired gastric accommodation. However, in healthy controls and in a sample of people in the community with functional dyspepsia, the maximum tolerated volume only explained 13 and 3% of variations in fasting and postprandial volumes, respectively, measured by SPECT (56). Thus there is still controversy whether the satiation test reflects exclusively gastric accommodation or a combination of accommodation, sensation, and emptying (32).

Ultrasonography

Imaging-based volume methods include analysis of surface geometry of human stomach by real-time, 3D ultrasonography or, most recently, by 3D reconstruction of images acquired by ordinary ultrasonography assisted by magnetic scan-head tracking (53, 78). In the most recent application of ultrasonography (54), an outline of the total stomach volume is visualized after ingestion of a liquid meal that serves as a contrast medium. 3D ultrasonography has been applied in adolescents and compared with simultaneously measured gastric volumes by SPECT; further validation and standardization are necessary (84).

Tests to Evaluate Gastric Contractility

Antropyloroduodenal manometry. The distal stomach, pylorus, and duodenum, with their relatively small diameters and ability to generate high-amplitude pressure activity, are suitable for manometric recordings. Antroduodenal manometry is available mainly at tertiary referral centers, and the test is invasive and time consuming and requires skilled technical support. Wireless motility capsules detect frequency and amplitude of phasic contractions during the process of capsule emptying from the stomach.

INDICATIONS. Indications for assessment of antropyloroduodenal motility by manometry are limited. In general, intubated manometry is not indicated when the underlying cause of dysmotility is already known (e.g., diabetes, scleroderma, amyloidosis) or when similar information can be obtained noninvasively. Thus the main indications for antroduodenal manometry are to evaluate whether the cause of documented gastric or small bowel transit is due to a neuropathy, myopathy, or unproven mechanical obstruction; to clarify whether there is a generalized or localized dysmotility in patients with dysmotility elsewhere (e.g., colonic inertia); and to clarify diagnosis in suspected chronic intestinal pseudo-obstruction syndromes.

METHOD. Water-perfused manometric catheters have a central lumen that is large enough to accommodate a guide wire. The guide wire is typically placed endoscopically or with the aid of fluoroscopy beyond the angle of Treitz, and the manometric catheter can be advanced over the guide wire through the pylorus, thus positioning sensors in the antrum and duodenum with fluoroscopic guidance. Experience from several centers suggests that sedation with midazolam (2–5 mg iv) followed by reversal with flumazenil (0.2–0.4 mg iv) does not result in any appreciable change in motility recordings, although there are no formal studies. Solid-state catheters are typically inserted with aid of fluoroscopy.

The intragastric sensors should be 1 cm or less apart. During the study, monitoring of the position of the tube relative to the location of the pylorus is crucial to ensure optimal measurements of distal antral contractile activity. The pylorus can be identified manometrically by one of three contractile patterns: a combination of distal antral (duration >5 s) and duodenal (duration <3 s) peaks; the presence of a high pressure zone ("tone"); or the lack of contractions in the tracing from the sensor distal to antral contractions, indicating the typical "quiescence" recorded from the larger diameter duodenal bulb. Continual recording of actual pyloric contractions is not generally needed, but the location of the pyloric recording helps facilitate proper assessment of distal antral contractility.

In anticipation of gastric accommodation, the tube is advanced by ~5 cm prior to starting the meal, which should contain at least 400 kcal to ensure a postprandial small intestinal response lasting at least 2 h (113). The solid-liquid meal should be balanced and typical of the average U. S. diet with 20–25% fat, 20–25% protein, and 50–55% carbohydrate. The ingestion of 400 calories is important, since a 2-h intestinal fed response [1 h per 200 kcal (107)] argues against an extrinsic neuropathy, whereas the return of phase III activity before the end of 2 h postprandially suggests an extrinsic neuropathy (45).

Careful monitoring of the waveforms is essential for optimal recordings; laboratory-based study with five sensors spaced 1 cm apart requires an average of five adjustments of tube location in the postprandial period to ensure accurate distal antral recordings. With the development of high-resolution manometry and catheters with 36 sensors that are 1 cm apart (Fig. 6, *left*), it is possible to perform ambulatory antroduodenal manometry (39) without the necessity for multiple adjustments of the tube's location (Fig. 6, *right*). This was a significant pitfall of solid-state antroduodenal manometry with three to five sensors, which were insufficient to accurately measure postprandial antral motility (62, 139).

INTERPRETATION. Normal motility consists of *1*) at least 1 MMC per 24 h; *2*) conversion to the fed pattern with a meal without return of MMC for at least 2 h after a 400 kcal meal; *3*) distal postprandial antral contractility [motility index (MI)/2 h >13.67]; *4*) small intestinal contractions exceeding 20 mmHg; and *5*) absence of abnormal patterns described below (47).

Manometry identifies certain "patterns" and some quantitative features of motility. Mechanical obstruction of the small intestine should be diagnosed radiologically, but if the obstruction is undetected by radiography, manometry may be of value by showing two patterns: postprandial nonpropagated clustered contractions (>30 min duration) separated by quiescence or simultaneous prolonged (>8 s) or summated contractions. No prospective study has evaluated sensitivity or specificity; the best data (47) included laparotomy in all patients suspected of having mechanical obstruction, and the positive predictive values of the two patterns relative to findings at laparotomy were 50 and 80%, respectively.

Myopathic disorders (e.g., scleroderma, amyloidosis, hollow visceral myopathy) are characterized by low-amplitude contractions (consistently <20 mmHg in small bowel) at the sites affected. Gut dilatation proximal to an obstruction may lead to low-amplitude recordings.

A reduced motility index of postprandial distal antral contractions (antral hypomotility) is significantly correlated with delayed gastric emptying of solids (prolonged lag time and $t_{1/2}$) in disease states (13) and pharmacological models of gastroparesis. Patients with scleroderma have average antral amplitude of <40 mmHg (135).

Postvagotomy, there is increased frequency (>3 during 3 h) of fasting MMCs in the duodenum while awake; the antral phase III of the MMC is often absent and there is postprandial antral hypomotility and a return of phase III activity within 2 h of the ingestion of a >400-kcal meal (45). In the Roux-en-Y syndrome, the efferent jejunal Roux limb shows uncoordinated bursts of phasic contractions or sustained uncoordinated pressure activity (87, 89).

Neuropathic disorders have been associated with antral hypomotility, abnormal propagation of the MMC, hypercontractility (bursts and sustained uncoordinated pressure activity),

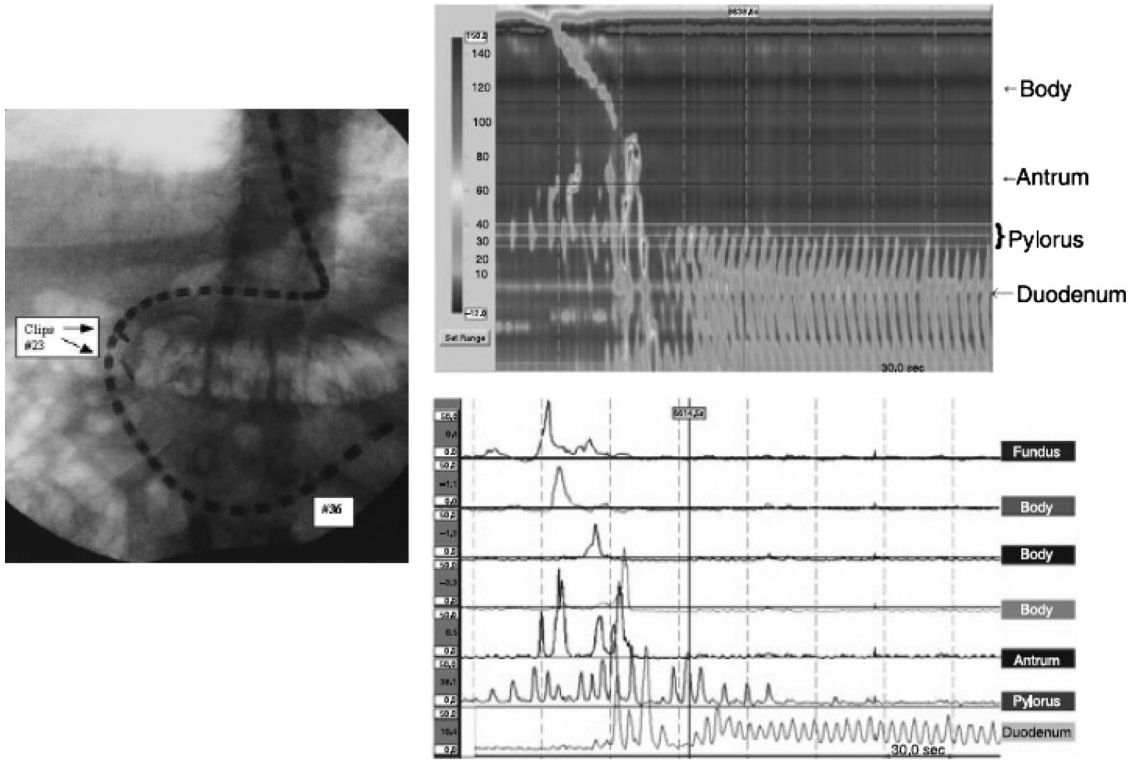

Fig. 6. *Left*: fluoroscopic image of catheter placed with the tip in the duodenum. Distal transducer, no. 36, is labeled (top arrow). Two clips, both within 1 cm proximal and distal to the pylorus, were placed prior to catheter insertion (bottom arrow). Data from transducer no. 23 in the pyloric channel were used as the standard for other cases in the interpretation of pyloric manometric and isocontour image data. *Right*: phase III of the migrating motor complex (MMC) using an Isocontour plot and manometry labeled from respective cavities. Phase III events were used to spatially identify the pylorus. Once the pylorus was identified, the region could be followed throughout the rest of the study. Pyloric position was periodically confirmed with fluoroscopy. *Top*: the isocontour plot and below is the corresponding manometric tracing. Shown to the left of the isocontour plot is the pressure-color key. To the right of the plot is a ruler to connect relationship between pressure wave and physical location along the length of the catheter. Reproduced from Desipio J, Friedenberg FK, Korimilli A, Richter JE, Parkman HP, Fisher RS. High-resolution solid-state manometry of the antropyloroduodenal region. *Neurogastroenterol Motil* 19: 188–195, 2007.

and failure of the intestine to develop the irregular but sustained contractions of normal amplitude that characterize the fed response. Manometric correlations with histopathology are poor, but they are either based on single reports or on incomplete analyses of either the manometric or the histological features (81) of cases of pseudo-obstruction.

Artifactual increases in intra-abdominal pressure at all levels of the upper gut are associated with regurgitation and typically occur postprandially in the rumination syndrome (6). A careful clinical history usually suffices to reach this diagnosis (22), especially if gastric emptying is normal and there is no gastroesophageal reflux in the supine position.

PITFALLS. Pitfalls confound the interpretation of GI manometry. Artifacts are characterized by simultaneous activity, e.g., cough, movement, or straining artifact. Detection of antral hypomotility may be compromised by displacement of the antral sensors out of the distal antrum. Several dysmotility syndromes may share common manometric features (e.g., "neuropathic" patterns); other disorders may exhibit, at different stages in the natural history, combinations of autonomic and enteric neuropathy (e.g., Parkinsonism plus or Shy-Drager syndrome) or enteric neuropathy and myopathy (e.g., amyloidosis and scleroderma). Abnormal motor patterns do not necessarily imply causation of the patient's symptoms. Stress related to the intubation and procedure may delay gastric emptying, impair antral contractility, suppress MMC cycling, and induce intestinal "irregularity." Gastric dysmotility may also be a consequence of vomiting (126), anorexia nervosa (3), or constipation (101). The technically demanding nature and pitfalls in interpretation of manometry have restricted its use to specialized GI motility centers.

The clinical impact of manometry has been documented in the pediatric age group, in which absence of MMCs predicts poor response to enteral feeding (41) or a prokinetic agent (64). In "outcome-based" studies, manometry influenced therapeutic approaches in 20% of patients with severe unexplained pain, nausea, and vomiting (114) or resulted in a new therapy in 12.6%, a new diagnosis in 14.9%, and referral to another specialist in 8% (133).

Other studies to measure gastric contractility noninvasively. MRI and dynamic antral scintigraphy (92, 131) have the potential to detect nonocclusive contractions. The wireless pH and motility capsule can detect pressure changes; one report in subjects with gastroparesis documented decreased frequency but not amplitude of contractions compared with normal (103). Experience with these alternate methods is extremely limited and not sufficient to replace manometry for the current limited indications.

Testing Gastric Myoelectrical Activity

Cutaneous electrogastrography (EGG) is commercially available with software/hardware packages. The EGG provides information about the gastric myoelectric frequency and the amplitude or power of the EGG signal in the normal or abnormal frequency ranges. However, optimal lead placement and interpretation of specific frequency and signal amplitude parameters are still debated. As with manometry, the EGG does not diagnose specific diseases. Abnormal EGGs are noted with nausea, vomiting, early satiety, anorexia, and dyspepsia including gastroparesis (2, 18), nonulcer dyspepsia (29), motion sickness (115), pregnancy (68), and eating disorders (3). Postprandial dysrhythmias and the lack of a postprandial increase in the power of the EGG signal may reflect delayed gastric emptying (19). EGG may define a gastric abnormality in a different subset of patients than those with emptying or manometry (57). The positive predictive value of abnormal EGG is estimated at 60–90% (96).

Indications. There is more controversy regarding the clinical indications for surface EGG than for other gastric motility tests. Proposed indications are for the evaluation of nausea, vomiting, postprandial abdominal pain, and postprandial abdominal bloating/distention and to assess gastric motor function in patients with chronic constipation or retching and nausea after fundoplication.

Method. EGG is performed after an overnight fast (15). Abdominal hair is shaved; the skin is prepared with gentle abrasion (as with gauze) or with an abrasive electrode paste. Alcohol and other drying organic solvents are not used on the skin as they can reduce electrical conduction. Recording electrodes are placed close to the antral region along the antral axis of the stomach to maximize signal-to-noise ratio. It is common is to place one sensor midway between xiphoid and umbilicus, and the others up and 30° to the left and down and 30° to the right. The patient needs to be in a comfortable reclining position or at a 45° angle in a quiet room throughout the study to prevent movement artifact that could be erroneously diagnosed as dysrhythmia. Multichannel recordings may enhance the information obtained with cutaneous EGG, such as the identification of slow-wave coupling (70, 123, 142).

The gastric myoelectrical signal is recorded with standard EKG-type electrodes. The signals of interest have frequencies of 1 cycle per minute (cpm) (0.018 Hz) to 12–15 cpm (0.25 Hz). The EGG signal must be amplified because it is of relatively low amplitude (200–500 μV). Filtering the signal to eliminate frequencies slower than 1 cpm or faster than 12–15 cpm eliminates signals from other sites such as cardiac, small intestinal, and colonic electrical activity artifacts, as well as respiratory and movement artifacts and electrical noise. Good filtering techniques do not preclude the need for motion-free recordings.

The fasting recording varies from 15 to 60 min; a standardized test meal of ~250–300 kcal (egg sandwich with 120 ml water or one can of Ensure) is given and is followed by postprandial recordings for 60–120 min. The raw signal is subjected to power-frequency spectral analysis to determine the frequency at any given time and the increase in signal power after meal ingestion. Under normal conditions, mean signal amplitude and power increases in the postprandial period are compared with fasting. The normal frequency is 2–4 cpm for at least 75% of the postprandial period (19, 96) or 2.4–3.6 cpm (69, 116). Dominant frequencies <2 and >4 cpm after a meal for $<25\%$ of the recording time probably indicates poor signal acquisition or signal noise rather than a true dysrhythmia. Harmonics of the baseline frequency (e.g., 6, 9 cpm) should be interpreted with caution.

Frequencies <2 cpm define bradygastria; frequencies >3.6 or 4 cpm and ≤ 9 cpm define tachygastria. An upper frequency filter serves to exclude electrical signals from the upper small intestine (typically 10–13 cpm). All patterns of dysrhythmia have been observed in idiopathic or diabetic gastroparesis, nausea of pregnancy, and motion sickness. Gastric dysrhythmias and symptoms as nausea and vomiting may occur in the absence of altered gastric

emptying (48). The EGG amplitude represents a weighted summation of gastric myoelectrical activity from the underlying stomach. The absolute amplitude (or power) of the signal may be affected by the patient's body habitus and electrode location. Usually, the postprandial to fasting power ratio value is >1 and may represent a true postprandial increase in the electrical (and presumably contractile) activity of the stomach or it may result from postprandial gastric distention (90). A power ratio of <1 may suggest a decreased gastric motor response to a meal. The distribution of EGG power summarizes the "absolute" signal amplitude in the bradygastria, normal rhythm, and tachygastria ranges (69).

EGG abnormalities seen in gastroparesis include (18, 20, 95) overall abnormal frequency, fasting or postprandially or during both periods, and decreased power ratio after a solid meal. Gastric dysrhythmias may be better indicators of symptoms such as nausea and early satiety than the gastric emptying rate and may better correlate with symptomatic responses to medications (97), but this requires confirmation.

Pitfalls. Pitfalls of surface EGG include startup costs for equipment, low reimbursement rates, and technical needs to conduct and interpret EGG. These factors limit the use of EGG to specialized centers. Transient dysrhythmia may not occur during the typical 1–2 h of laboratory-based recording; on the other hand, ambulatory EGG recordings may include motion artifact. The significance of EGG abnormalities relative to gastric emptying remains unclear. The physiological significance of fasting dysrhythmias is unclear. Hyperglycemia may induce EGG abnormalities (66).

EGG appears to complement gastric emptying studies and antroduodenal manometry in the evaluation of patients with elusive symptoms referable to the upper GI tract. An EGG is not usually needed if gastric emptying is delayed. Studies have evaluated EGG in healthy subjects (98), in patients with motility-like dyspepsia (29), chronic intestinal pseudo-obstruction (33, 40), and chronic constipation (100) and after gastrectomy (63). EGG findings have also been correlated with scintigraphy (19), manometry (118), or ultrasound (99).

Validation and application of EGG in animals. There are several papers documenting the use of EGG to measure gastric electrical rhythm in large animals (91).

Conclusions

Table 1 compares several of the characteristics of the main techniques discussed in this article. Although there have been some studies comparing two methods simultaneously, allowing direct comparison or validation (e.g., ^{13}C breath tests and scintigraphy, or barostat and SPECT, or SPECT and MRI), comparisons of the different methods are often difficult because different techniques use different "standard" test meals.

Standardization of scintigraphic gastric emptying tests across medical centers and continued validation of wireless pH and motility capsule and gastric emptying breath tests represent significant advances in making tests of gastric emptying safer and more readily available. The development of MRI, SPECT with simultaneous assessment of gastric emptying, and advanced ultrasonography may permit more comprehensive studies of pathophysiology of gastric diseases. Noninvasive assessment of gastric contractility with imaging lags behind the other methods, but has the potential to detect nonocclusive contrac-

Table 1. *Comparison of methods to measure gastric motor functions in vivo in humans*

	Scintigraphy	Stable isotope breath test	Electrogastrography	Antroduodenal manometry	Wireless pressure and pH capsule	Barostat	SPECT	MRI
Indication/ function measured	Gastric emptying	Gastric emptying	Gastric electrical rhythm	Antral, duodenal pressure profiles and amplitude	Emptying and pressure amplitude	Gastric tone, accommodation	Gastric volume accommodation	Gastric volume accommodation
Device, assembly or special requirements	External gamma camera and isotope-labeled meal	Breath collection vials and stable isotope-labeled meal	Recording device	Perfusion- or solid-state system±sleeve for sphincters + recorder	Intraluminal capsule with miniaturized strain gauge and pH measurement	External barostat and pressure/ volume recording	Standard external SPECT camera and IV isotope	Standard external MRI camera and oral contrast.
Placement of device			Surface electrodes	Tube placed via endoscopy/fluoroscopy	Capsule swallowed	Large volume balloon and tube	IV injection	IV injection
Performance/versatility/ interpretation	Excellent, standardized meals, data acquisition and interpretation	Becoming standardized; performance related to mathematics analysis	Standard acquisition, endpoints identified measurable but unclear significance	Technically challenging; partly quantitative, operator dependent	Standard acquisition, delayed emptying fairly valid; pressures of unclear significance	Technically challenging, mainly research	Excellent standardization and validation; mainly research	Excellent standardization; some validation; mainly research
Duration of study	Typically 4 h, could be added to small bowel and colon transit	3-4 h	Usually 30 min fasting, 60 min postmeal	Fasting (4 h) and postmeal (2 h), limited to proximal small bowel	6 h, could be added to small bowel and colon transit	Usually 30 min fasting, 90 min postmeal	15 min fasting, 30 min postmeal	15 min fasting, 30 min postmeal
Availability/ potential use	+	+++	+	Specialty	+	Research	Specialty	Specialty
Costs	++	+	++	+++	++	Not clinical	++	+++++

SPECT, single photon emission computed tomography; IV, intravenous.

tions and represents a potential advance over manometric methods. High-resolution manometry reduces the technical pitfalls of antroduodenal manometry.

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