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The Wireless Motility Capsule: a One-Stop Shop for the Evaluation of GI Motility Disorders

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Abstract The wireless motility and pH capsule (WMC) provides an office-based test to simultaneously assess both regional and whole gut transit. Ingestion of this non-digestible capsule capable of measuring temperature, pH, and the pressure of its immediate surroundings allows for the measurement of gastric, small bowel, and colonic transit times in an ambulatory setting. Approved by the US Food and Drug Administration for the evaluation of suspected conditions of delayed gastric emptying and the evaluation of colonic transit in chronic idiopathic constipation, WMC should be considered in suspected gastrointestinal motility disorders as it provides a single study capable of simultaneously assessing for regional, multiregional, or generalized motility disorders. Specific indications for testing with the WMC should include the evaluation of suspect cases of gastroparesis, small bowel dysmotility, and slow transit constipation, as well as symptom syndromes suggestive of a multiregional or generalized gastrointestinal transit delay.

Keywords Wireless motility capsule · Smartpill · Gastroparesis · Gastric emptying time · Small bowel transit time · Colon transit time

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Introduction

The assessment of gastrointestinal transit and motility is frequently needed to define underlying abnormal physiology and direct therapy for common functional gastrointestinal disorders including gastroparesis, functional dyspepsia, chronic idiopathic constipation, and irritable bowel syndrome failing empiric medical therapy. Traditional transit testing has largely relied on nuclear or radiographic imaging modalities. The most widely employed test for the assessment of gastric emptying is gamma camera scintigraphy. Scintigraphy involves the ingestion of a low-fat, egg-white radiolabeled with a technetium sulfur colloid, toast, jam, and water with imaging using a gamma camera immediate following meal ingestion as well as 1, 2, and 4 h post-meal ingestion [1]. Breath testing utilizing a stable carbon isotope [13] C-labeled substrate (octanoate or Spirulina) that is ingested as part of a solid meal, digested, absorbed, and later released as labeled carbon dioxide provides a promising alternative to scintigraphy for the assessment of solid gastric emptying [2, 3]. Although [13] C breath testing is widely used in Europe, it is not yet available in the USA for the assessment of gastric emptying.

The assessment of small bowel transit has been described utilizing gamma camera scintigraphy, lactulose breath testing and barium radiography. Small bowel scintigraphy is typically performed as part of whole gut transit scintigraphy utilizing radiolabeled water [4], resin beads, or a solid meal [5]. However, scintigraphy is limited to a few academic centers and lacks standardization as a means of assessing small bowel transit. Lactulose breath testing has also been described for the assessment of small bowel transit, typically reported as an orocecal transit time [6]. However, this modality lacks accuracy in defining small bowel transit time. Barium radiography represents one of the oldest modalities used to assess small bowel transit time. However, many limitations of this testing

modality have also been identified, most notably its lack of standardization and definition of normal small bowel transit [7, 8].

The assessment of colonic transit time is most commonly performed using a radiopaque marker (ROM) study. ROM entails the ingestion of multiple small radiopaque markers and the pursuit of one or more abdominal radiographs to follow the movement of the markers through the digestive tract. A 5-day ROM protocol can be performed to simply distinguish a delayed colon transit from that of normal colon transit [9]. A more complex 7-day ROM protocol provides a more precise calculation of colon transit time as well as information on segmental colon transit [10]. An alternative means of colonic transit testing is with use of scintigraphy, capable of providing transit information regarding segmental colon and total colon transit time. Two scintigraphic methodologies to assess colon transit have been described either using resin beads containing radiolabeled charcoal [11] or radiolabeled water [4].

The wireless motility and pH capsule (WMC) is an orally ingested, non-digestible capable of measuring gastric emptying time, small bowel transit time, and colon transit time as a single study. This review will include WMC characteristics and testing protocol, performance of the WMC compared to traditional transit testing modalities, its limitations and adverse effects, and its clinical indications as well as diagnostic utility.

WMC System

The wireless motility and pH monitoring system (Smartpill®) consists of a single-use capsule measuring 26.8 × 11.7 mm, a receiver, and data processing software (Fig. 1). The capsule possesses sensors that continuously monitor the temperature, pH, and pressure of its immediate surrounds which are transmitted via radio waves to an external receiver kept within 5 ft of the body. Characteristic patterns in the recorded temperature and pH during the course of the study are then used to determine the movement of the capsule through the digestive tract including its time of arrival into the stomach, time of arrival in the small intestine, time of arrival into the cecum, and exit from the body during defecation. From this information, a precise determination of gastric emptying time (GET), small bowel transit time (SBTT), and colon transit time (CTT) can be made [12] (Fig. 2). Normative values have been determined to be 2 to 5 h for GET, 2 to 6 h for SBTT, and 10 to 59 h for CTT [13] (Table 1). However, gender, age, and country of origin have been recently shown to impact regional transit times in a cohort of 215 healthy volunteers (191 from the USA and 40 from Sweden) [14]. Female gender was associated with a longer GET by 17 min, $P = 0.0307$, and longer CTT by 104 min, $P = 0.0285$. Increasing age was associated with a shorter small bowel transit. It is also important to realize that unlike gastric emptying scintigraphy and breath testing, which are measuring the gastric emptying of digestible solids, the WMC is measuring the emptying of a non-digestible solid. As such, the WMC is not affected by the fed contraction and must therefore wait for return of fasting motor activity to pass across the pylorus and into the duodenum [15].

Fig. 1 Wireless motility and pH capsule monitoring system. Photo is Copyright© 2001–2016 Given Imaging Ltd. Reprinted by permission

Intraluminal pressure recordings also provide data on the frequency of contractions and strength of contractions as the capsule travels through the gut lumen as a single pressure recording device. Normative values have been reported for a variety of intraluminal pressure characteristics in the stomach and small bowel, including contraction frequency, contraction amplitude, and a motility index [16].

WMC Protocol

WMC testing begins with an overnight fast, the avoidance of tobacco and alcohol, and the discontinuation of medications potentially altering gastric pH and gastrointestinal motility (Fig. 3). A standardized meal either consisting of a 260-kcal nutrient bar (17 % protein, 66 % carbohydrates, 2 % fats, and 3 % fiber) that is available through the manufacturer along with 50 ml of water or that of a low fat egg substitute meal (120 g eggbeaters, two slices of bread, 30 g of strawberry jam, and 120 ml of water) is consumed. It is important not to deviate from the standardized meal, as the use of an alternative meal has been shown to affect gastric emptying time [17]. The WMC is activated and calibrated using an activation fixture provided by the manufacturer and immediately swallowed following the completion of the standardized meal. It is important to note that the ingestion of the WMC prior to consuming the standardized meal has been shown to lengthen the GET by 52 min ($P = 0.0063$) and shorten CTT by 140 min ($P = 0.0189$) underscoring the importance of adherence to the

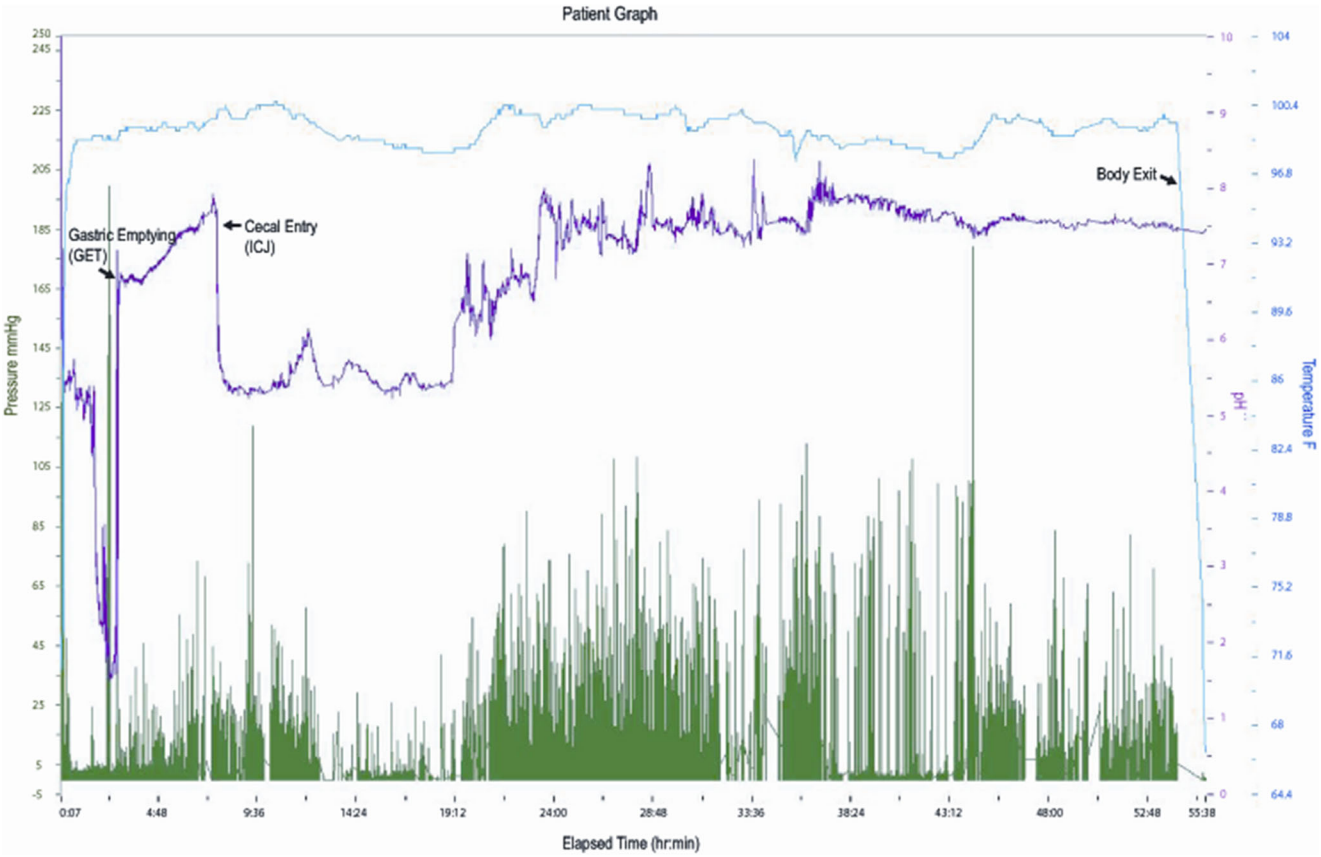

Fig. 2 WMC tracing. Gastric emptying time: period of time ranging from abrupt rise in temperature to abrupt rise in pH by at least 3 units. Small bowel transit time: period of time ranging from abrupt rise in pH to abrupt drop in pH by 1 unit that is sustained for at least 10 min (at least 30 min after gastric emptying). Colon transit time: period of time ranging from abrupt 1-unit drop in pH to abrupt drop in temperature [12]

standardized meal [14]. An external data recorder is attached to the body via a belt worn around the waist. This recorder needs to be kept within 5 ft of the body for the 3- to 5-day testing period. Various activities such as meals, sleep, and bowel movements are manually recorded during the testing period via an event button on the data receiver. The patient can leave the office following capsule ingestion but must wait 6 h from the time of capsule ingestion before eating another meal. This period of brief fasting is very important as early eating can impact the gastric emptying time owing to the fact that the WMC assesses emptying of a non-digestible solid and must wait for the return of fasting motor activity of the stomach to pass through the pylorus. The patient must also refrain from the use of tobacco products for 8 h and the ingestion of alcohol for 72 h post-WMC ingestion. There are no further restrictions regarding subsequent meals during the testing period, although strenuous or vigorous exercise must be avoided. The receiver is then returned to the office upon study completion.

Table 1 Normative WMC transit times

Gastric emptying time	2–5 h
Small bowel transit time	2–6 h
Colon transit time	10–59 h

From [13]

WMC Clinical Trial Results

Gastric emptying time (GET) as measured by the WMC was directly compared to gastric emptying scintigraphy in 87 healthy adults aged 18–75 and 61 adults aged 18–75 with

- Discontinuation of medications raising gastric pH
  - Proton pump inhibitors 7 days prior
  - Histamine receptor antagonists 3 days prior
  - Antacids 1 day prior
- Discontinuation of medications slowing GI motility 3 days prior
  - Anticholinergic agents
  - Antidiarrheal agents
  - Antiemetic agents
  - Narcotic analgesic agents
- Discontinuation of medications accelerating GI motility
  - Prokinetic agents 3 days prior
  - Laxative agents 2 days prior
- Discontinuation of nonsteroidal anti-inflammatory agents 3 days prior
- Avoidance of tobacco products for 8 hours prior
- Avoidance of alcohol consumption for 24 hours prior

Fig. 3 Preparation for WMC testing [34•]

gastroparesis in an industry-sponsored multicenter trial [18]. In this study, GET measured by WMC compared favorably with gastric emptying scintigraphy at 2 and 4 h with a correlation coefficient of 0.63 with 0.73, respectively. This study also demonstrated a diagnostic accuracy of 0.83 with GET compared to 0.79 with scintigraphic emptying at 2 h and 0.82 for scintigraphic gastric emptying at 4 h. GET as measured by WMC was also found to correlate accurately with gastric emptying scintigraphy in single center study involving ten healthy adults aged 18–65 with a correlation coefficient of 0.9 at 2 h and 0.72 at 4 h post-meal ingestion [19]. Another single-center study, this time involving 22 children aged 8–17, found the WMC to have 100 % sensitivity and 50 % specificity in predicating gastroparesis as compared to scintigraphic gastric emptying at 2 h. Furthermore, the WMC detected motor abnormalities in 17 patients compared with ten patients assessed by antroduodenal manometry [20•].

Small bowel transit time (SBTT) as measured by the WMC has been directly compared to small bowel transit obtained during whole gut scintigraphy in an industry-sponsored multicenter trial involving 66 healthy adults aged 18–65 and 34 adults aged 18–66 with gastroparesis [21]. In this study, the measured SBTT by WMC was similar to the calculated SBTT by scintigraphy for both the healthy controls and the gastroparetics. A single-center study of ten healthy adults aged 18–65 undergoing simultaneous WMC testing and whole gut scintigraphy has also demonstrated comparable SBTT measurements with that of scintigraphy [19]. It is important to note that in the clinical trials, the determination of SBTT was not possible in 5–10 % of the WMC studies due to an inability to accurately identify the necessary pH landmarks.

Colon transit time (CTT) as measured by the WMC has been directly compared to colon transit obtained by simultaneous 2- and 5-day radiopaque marker (ROM) testing in an industry-sponsored multicenter clinical trial involving 78 adults aged 21–79 meeting Rome II criteria for functional constipation and 87 healthy adults aged 18–65 [22]. In this study, CTT as measured by the WMC demonstrated an overall correlation coefficient of 0.78 with the number of retained radiopaque markers at day 2 and correlation coefficient of 0.59 with the number of retained markers at day 5. A follow-up industry-sponsored multicenter trial was performed on 158 adults aged 18–80 meeting modified Rome III criteria for constipation [23]. In this study, delayed CTT by WMC (defined as CTT > 59 h) demonstrated an overall agreement of 87 % between with that of 5-day ROM (defined as CTT > 67 h). A single-center study has also been performed on 27 elderly adults aged 65–78 fulfilling Rome III criteria for chronic functional constipation and 11 healthy elderly adults aged 67–76 [24•]. In this study, device agreement between WMC and 5-day ROM in identifying slow colonic transit was 88 %, with slow transit constipation identified in 32 % by WMC versus 28 % by ROM.

Whole gut transit time (WGTT) as measured by the WMC was directly compared to whole gut transit scintigraphy demonstrating comparable transit results [19]. In this study, ten healthy adults consumed a dual isotope gastric emptying meal followed immediately by ingestion of the WMC. After removing a single outlier with rapid WMC transit and very slow isotope excretion, the correlation coefficient of WGTT as measured by the WMC was 0.79 with that of whole gut scintigraphy.

There is also data regarding the reproducibility of the regional transit times as measured by the WMC. A recent clinical trial assessing the intrasubject variability of SBTT and CTT was performed on ten healthy adults aged 18–26 who were required to ingest two capsules 24 h apart [25•]. This study revealed an intrasubject coefficient of variation (COV) of 12.0 % for the SBTT and 25.8 % for CTT as measured by the WMC. The intrasubject variability of the SBTT by WMC was better than that of scintigraphy (COV of 19 %) and that of the lactulose breath test (mean COV of 18.5, 29.7, and 28.3 % with 10, 15, and 20 g of lactulose, respectively) [26]. Intrasubject variability for CTT was similar to the intrasubject variability of scintigraphy (COV of 14–28 %) [27]. Intrasubject variability has not been reported for GET as measured by the WMC; however, intersubject variability is similar to that of gastric emptying scintigraphy at 2 h and higher than that at 4 h in healthy adults with a COV of 28 % versus 29 and 8 %, respectively [18, 27].

WMC Indications

The WMC has been approved by the US Food and drug Administration (FDA) for the evaluation of suspected conditions of delayed gastric emptying since 2006, and for the evaluation of colonic transit in chronic idiopathic constipation since 2009. The American and European Neurogastroenterology and Motility Societies (ANMS and ESNM) have outlined the clinical indications for use of the WMC in a position paper published in 2011 [28]. These indications include (1) the assessment of gastric emptying (as well as regional and whole gut transit time) in suspected cases of gastroparesis and symptoms of upper gastrointestinal (GI) dysmotility, (2) the assessment of small bowel transit to specifically facilitate the detection of small bowel dysfunction in more generalized GI motility disorders, and (3) the assessment of colonic transit time in cases of chronic constipation. The ANMS and ESNM also concluded that the WMC was particularly useful in cases of suspected alterations of GI motility involving more than one region of the GI tract.

A systematic review assessed the comparative effectiveness of WMC with other tests of gastric and colonic motility [29]. This review was funded by the Agency for Healthcare Research and Quality and published by the Johns Hopkins Evidence-based Practice Center. The investigators concluded

that WMC is comparable to other transit testing modalities for the detection of delayed gastric emptying and slow-transit constipation. They added that the overall strength of evidence regarding the detection, diagnosis, treatment, and management of gastric and colonic dysmotility disorders was either low or insufficient for making evidence-based recommendations. As such, they further concluded that that there was insufficient data to determine the optimal timing of WMC in diagnostic algorithms.

WMC Use in Special Populations

As already discussed, WMC has demonstrated use in the assessment of motility disorders in the elderly and pediatric populations [20•, 24•]. The WMC has also been shown to be safe and effective in assessing regional and whole gut transit time in adults with spinal cord injury (SCI) [30]. In the study, 20 adults aged 24 to 63 with either complete or incomplete paraplegia or tetraplegia for six or more months were matched to age and gender able-bodied controls. Consistent with previous reports, those with SCI revealed prolonged GET, CTT, and WGTT compared to controls. The WMC may have a potential role in the management of cystic fibrosis given its ability to provide a gastrointestinal pH and transit profile in this population [31]. This was demonstrated in a study of ten adults with cystic fibrosis aged 18–27 who were compared to ten aged match controls and found to have significantly delayed small intestinal transit as well as a deficient buffering capacity needed to neutralize gastric acid in the proximal small bowel. The WMC was also safely administered to eight critically ill trauma patients in a clinical trial to assess gastric and small bowel transit [32]. Compared to the results of 87 healthy controls from a separate study, the trauma patients were found to have significant delays in both gastric and small bowel transit.

WMC Pressure Data

A unique feature of the WMC is the device's ability to sense the pressure of its immediate surroundings and report a pressure ranging from 0 to 350 mmHg every 0.5 s for the initial 24 h and every second thereafter. This allows for the measurement of intraluminal contractile frequency and strength as the WMC passes through stomach, small bowel, and colon, and may help to characterize contractile abnormalities in addition to providing transit data. However, such contractile data is limited by the WMC being a single pressure sensor that is constantly moving through the GI tract, precluding any assessment of peristaltic wave propagation. Although normal pressure patterns have been characterized in healthy controls, and abnormal pressure patterns identified in some cases of gastroparesis [16] and chronic constipation [33], a well-defined clinical role for the WMC pressure data has not been established.

WMC Contraindications

Due to concerns for capsule retention within the GI tract, WMC testing should not be performed in those with swallowing disorders, dysphagia to solid foods or pills, history of gastric bezoar, suspected or known strictures or fistulas within the GI tract, Crohn's disease, history of diverticulitis, history of surgery on the gastrointestinal tract, or any abdominal or pelvic surgery within the last 3 months. Also, due to concerns related to the capsule's radio transmission of data to the receiver, the WMC is contraindicated in those with a cardiac pacemaker or defibrillator. However, the test is permitted in those with a gastric stimulator, bladder stimulator, spinal stimulator, and infusion pumps for medication including insulin pumps and continuous glucose monitors. Capsule passage must also be radiographically confirmed prior to the pursuit of magnetic resonance imaging if passage from the body has not been previously confirmed by the temperature curve during the study or visualized passage from the body during a bowel movement. The WMC is not approved for use in the pediatric population and is presently confined to clinical trials in this population.

WMC Adverse Events

Test failure can occur due to an inability of the patient to swallow the capsule, failure of the WMC to transmit data, failure of the receiver to record or download data, and/or software malfunction. The incidence of patient failure to swallow in the clinical trials was 0.6 %. Post-marketing analysis has revealed and incidence of equipment failure of approximately 0.8–0.9 %.

Inability to confirm passage of the capsule outside the body, capsule retention and obstruction represent the most serious potential adverse events with the WMC. In the clinical trials, there were several incidents of prolonged capsule retention with all but two cases demonstrating spontaneous passage of the capsule by X-ray imaging 21 days post-capsule ingestion. In one of the two remaining cases of capsule retention, the retained capsule in the stomach passed into the small bowel with a single dose of intravenous erythromycin. In the second case, capsule retention occurring in the stomach due to a peptic stricture in the proximal duodenum required capsule extraction via upper endoscopy. Since commercial introduction of the WMC, with over 10,000 capsule shipped for clinical use, there have been isolated reports of capsule retention requiring intervention at an estimated rate of 0.01 % [34•]. Cases of capsule retention in the stomach have either responded to the administration of a prokinetic agent or required upper endoscopy for capsule extraction when the

prokinetic agent failed. In two cases of small bowel capsule retention, surgical intervention was required due to the presence of a small bowel tumor that had not been previously diagnosed. In another case of small bowel capsule retention in a small bowel diverticulum, the WMC passed 2 months later with the use of prokinetic and laxative therapy. In the cases of prolonged capsule retention in the colon, the capsule either passes spontaneously or with the use of laxatives. In the event capsule passage outside the body cannot be confirmed at the end of the 5-day testing period, the management approach should be based on suspected capsule location (from the pH profile obtained during the study). Given the low risk of capsule obstruction once in the colon, there is no specific follow-up necessary for colonic capsule retention. If capsule retention is suspected to be in the stomach or small bowel, serial X-ray imaging is recommended and should be repeated at 3-week intervals until the capsule has moved into the colon or exited the body. If clinical evidence of obstruction with symptoms of nausea, vomiting, abdominal pain, or abdominal distention develops, abdominal imaging should be pursued immediately and capsule extraction pursued.

WMC Clinical Utility

From a practical standpoint, the WMC should be considered the transit study of choice when a generalized or multiregional motility disorder is clinically suspected. This may eliminate the need for additional regional motility testing as well as influence the diagnosis and treatment strategy. Furthermore, there is growing evidence that a substantial proportion of those suspected of having isolated regional transit delays such gastroparesis, intestinal dysmotility, or slow transit constipation are found to have multiregional and generalized transit delays. Kuo and colleagues reported their findings from a retrospective review of 83 patients from two academic centers who underwent WMC testing [35]. WMC provided complete and interpretable data in 77 of the 83 patients. WMC provided a new diagnosis in 44 (53 %) of the cases and specifically a new generalized motility disorder in 23 (28 %) of patients. Presenting symptoms did not predict a normal versus isolated versus generalized motility disorder as determined by the WMC. Furthermore, WMC testing influenced management in 67 % of cases and eliminated the need for additional testing including gastric scintigraphy in 17 %, barium radiography in 54 %, and ROM testing in 68 %.

Rao and colleagues have reported similar findings in 86 patients from a single tertiary care center undergoing WMC as well as conventional motility testing for suspected motility disorders (42 % with suspected upper GI dysmotility and 58 % with suspected lower GI dysmotility) [36]. WMC testing provided new diagnostic information in 47 % of those with suspected lower GI dysmotility and 53 % of those with suspected upper GI dysmotility. Furthermore, a generalized motility disorder was identified in 51 % of patients, influencing management in 50 % of those with suspected upper GI dysmotility and 30 % of those with lower GI dysmotility.

Arora and colleagues reported on the diagnostic yield and clinical utility of WMC test results from a retrospective chart review of 166 patients with symptoms suggestive of a multiregional GI dysmotility [37•]. Of the 166 patients tested, complete interpretable WMC data was obtained from 161 patients. Multiregional dysmotility was diagnosed in 54 patients with another 55 identified as having isolated regional motility disorders. Past medical history, past surgical history, and presenting symptom were unable to predict a regional versus multiregional motility disorder.

Conclusions

The WMC provides the clinician with an office-based, radiation free, standardized testing modality capable of simultaneously measuring gastric emptying time, small bowel transit time, and colon transit time. WMC has demonstrated comparable results with traditional radiolabeled and radiographic motility testing modalities. WMC should be considered as an alternative for transit testing in suspected cases of gastroparesis, small bowel dysmotility, and colon transit testing, and considered the test of choice in suspected conditions of multiregional or generalized motility disorders.

Compliance with Ethics Guidelines

Conflict of Interest Richard J. Saad declares that he has no conflicts of interest.

Human and Animal Rights and Informed Consent With regard to the author's research cited in this paper, all procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. In addition, all applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

References

Papers of particular interest, published recently, have been highlighted as:

- Of importance

1. Abell TL, Camilleri M, Donohoe K, et al. Consensus recommendations for gastric emptying scintigraphy: a joint report of the American neurogastroenterology and motility society and the society of nuclear medicine. Am J Gastroenterol. 2008;103:753–63.

2. Szarka LA, Camilleri M, Vella A, et al. A stable isotope breath test with a standard meal for abnormal gastric emptying of solids in the clinic and in research. Clin Gastroenterol Hepatol. 2008;6:635–43. e1.
3. Delbende B, Perri F, Couturier O, et al. 13C-octanoic acid breath test for gastric emptying measurement. Eur J Gastroenterol Hepatol. 2000;12:85–91.
4. Bonapace ES, Maurer AH, Davidoff S, Krevsky B, Fisher RS, Parkman HP. Whole gut transit scintigraphy in the clinical evaluation of patients with upper and lower gastrointestinal symptoms. Am J Gastroenterol. 2000;95:2838–47.
5. Argenyi EE, Soffer EE, Madsen MT, Berbaum KS, Walkner WO. Scintigraphic evaluation of small bowel transit in healthy subjects: inter- and intrasubject variability. Am J Gastroenterol. 1995;90:938–42.
6. Wilberg S, Pieramico O, Malfertheiner P. The H2-lactulose breath test in the diagnosis of intestinal transit time. Leber Magen Darm. 1990;20:129–37.
7. Gollub MJ. When doing a small-bowel series, what is considered a normal transit time for barium to reach the cecum? AJR Am J Roentgenol. 2000;174:866.
8. Szarka LA, Camilleri M. Methods for the assessment of small-bowel and colonic transit. Semin Nucl Med. 2012;42:113–23.
9. Hinton JM, Lennard-Jones JE, Young AC. A new method for studying gut transit times using radioopaque markers. Gut. 1969;10:842–7.
10. Metcalf AM, Phillips SF, Zinsmeister AR, MacCarty RL, Beart RW, Wolff BG. Simplified assessment of segmental colonic transit. Gastroenterology. 1987;92:40–7.
11. Burton DD, Camilleri M, Mullan BP, Forstrom LA, Hung JC. Colonic transit scintigraphy labeled activated charcoal compared with ion exchange pellets. J Nucl Med. 1997;38:1807–10.
12. Saad RJ, Hasler WL. A technical review and clinical assessment of the wireless motility capsule. Gastroenterol Hepatol (N Y). 2011;7:795–804.
13. Lee YY, Erdogan A, Rao SS. How to assess regional and whole gut transit time with wireless motility capsule. J Neurogastroenterol Motil. 2014;20:265–70.
14. Wang YT, Mohammed SD, Farmer AD, et al. Regional gastrointestinal transit and pH studied in 215 healthy volunteers using the wireless motility capsule: influence of age, gender, study country and testing protocol. Aliment Pharmacol Ther. 2015;42:761–72.
15. Cassilly D, Kantor S, Knight LC, et al. Gastric emptying of a non-digestible solid: assessment with simultaneous SmartPill pH and pressure capsule, antroduodenal manometry, gastric emptying scintigraphy. Neurogastroenterol Motil. 2008;20:311–9.
16. Kloetzer L, Chey WD, McCallum RW, et al. Motility of the antroduodenum in healthy and gastroparetics characterized by wireless motility capsule. Neurogastroenterol Motil. 2010;22:527–33. e117.
17. Willis HJ, Thomas W, Willis DJ, Slavin JL. Feasibility of measuring gastric emptying time, with a wireless motility device, after subjects consume fiber-matched liquid and solid breakfasts. Appetite. 2011;57:38–44.
18. Kuo B, McCallum RW, Koch KL, et al. Comparison of gastric emptying of a nondigestible capsule to a radio-labelled meal in healthy and gastroparetic subjects. Aliment Pharmacol Ther. 2008;27:186–96.
19. Maqbool S, Parkman HP, Friedenberg FK. Wireless capsule motility: comparison of the SmartPill GI monitoring system with scintigraphy for measuring whole gut transit. Dig Dis Sci. 2009;54:2167–74.
20.• Green AD, Belkind-Gerson J, Surjanhata BC, Mousa H, Kuo B, Di Lorenzo C. Wireless motility capsule test in children with upper gastrointestinal symptoms. J Pediatr. 2013;162:1181–7. **This is the first reported study demonstrating safety and efficacy in a pediatric population**.
21. Sarosiek I, Selover KH, Katz LA, et al. The assessment of regional gut transit times in healthy controls and patients with gastroparesis using wireless motility technology. Aliment Pharmacol Ther. 2010;31:313–22.
22. Rao SS, Kuo B, McCallum RW, et al. Investigation of colonic and whole Gut transit with wireless motility capsule and radioopaque markers in constipation. Clin Gastroenterol Hepatol. 2009;7(5):537–44.
23. Camilleri M, Thorne NK, Ringel Y, et al. Wireless pH-motility capsule for colonic transit: prospective comparison with radiopaque markers in chronic constipation. Neurogastroenterol Motil. 2010;22:874–82. e233.
24.• Rao SS, Coss-Adame E, Valestin J, Mysore K. Evaluation of constipation in older adults: radioopaque markers (ROMs) versus wireless motility capsule (WMC). Arch Gerontol Geriatr. 2012;55:289–94. **This is the first study to demonstrate safety and efficacy of the WMC in an elderly population**.
25.• Mikolajczyk AE, Watson S, Surma BL, Rubin DT. Assessment of tandem measurements of pH and total Gut transit time in healthy volunteers. Clin Transl Gastroenterol. 2015;6:e100. **This study demonstrates similar reproducibility with small bowel an colonic transit time as measured by the WMC as compared to traditional transit testing including lactulose breath testing and scintigraphy**.
26. La Brooy SJ, Male PJ, Beavis AK, Misiewicz JJ. Assessment of the reproducibility of the lactulose H2 breath test as a measure of mouth to caecum transit time. Gut. 1983;24:893–6.
27. Cremonini F, Mullan BP, Camilleri M, Burton DD, Rank MR. Performance characteristics of scintigraphic transit measurements for studies of experimental therapies. Aliment Pharmacol Ther. 2002;16:1781–90.
28. Rao SS, Camilleri M, Hasler WL, et al. Evaluation of gastrointestinal transit in clinical practice: position paper of the american and european neurogastroenterology and motility societies. Neurogastroenterol Motil. 2011;23:8–23.
29. Stein E, Clarke JO, Hutfless S, et al. 2013.
30. Williams 3rd RE, Bauman WA, Spungen AM, et al. SmartPill technology provides safe and effective assessment of gastrointestinal function in persons with spinal cord injury. Spinal Cord. 2012;50:81–4.
31. Gelfond D, Ma C, Semler J, Borowitz D. Intestinal pH and gastrointestinal transit profiles in cystic fibrosis patients measured by wireless motility capsule. Dig Dis Sci. 2013;58:2275–81.
32. Rauch S, Krueger K, Turan A, You J, Roewer N, Sessler DI. Use of wireless motility capsule to determine gastric emptying and small intestinal transit times in critically ill trauma patients. J Crit Care. 2012;27:534 e7–12.
33. Hasler WL, Saad RJ, Rao SS, et al. Heightened colon motor activity measured by a wireless capsule in patients with constipation: relation to colon transit and IBS. Am J Physiol Gastrointest Liver Physiol. 2009;297:G1107–14.
34.• Hasler WL. The use of SmartPill for gastric monitoring. Expert Rev Gastroenterol Hepatol. 2014;8:587–600. **This is a comprehensive review on the current and future use of the WMC in the evaluation and management of gastroparesis and other antroduodenal motility disorders**.
35. Kuo B, Maneerattanaporn M, Lee AA, et al. Generalized transit delay on wireless motility capsule testing in patients with clinical suspicion of gastroparesis, small intestinal dysmotility, or slow transit constipation. Dig Dis Sci. 2011;56(10):2928–38.
36. Rao SS, Mysore K, Attaluri A, Valestin J. Diagnostic utility of wireless motility capsule in gastrointestinal dysmotility. J Clin Gastroenterol. 2010;5(4):249–60.
37.• Arora Z, Parungao JM, Lopez R, Heinlein C, Santisi J, Birgisson S. Clinical utility of wireless motility capsule in patients with suspected multiregional gastrointestinal dysmotility. Dig Dis Sci. 2015;60:1350–7. **This is the largest study to demonstrate the diagnostic value of the WMC in case of multiregional GI dysmotility syndromes**.