Emerging wearable technology applications in gastroenterology: A review of the literature

Kimberly PL Chong, Benjamin KP Woo

ORCID number: Kimberly PL Chong 0000-0003-1897-5351; Benjamin KP Woo 0000-0002-0127-4850.

Author contributions: Chong KPL and Woo BKP both performed the collection of data and contributed to the manuscript drafting.

Conflict-of-interest statement: The authors declare no conflict of interests.

Open-Access: This article is an open-access article that was selected by an in-house editor and fully peer-reviewed by external reviewers. It is distributed in accordance with the Creative Commons Attribution NonCommercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited and the use is non-commercial. See: http://creativecommons.org/Licenses/by-nc/4.0/

Manuscript source: Invited manuscript

Specialty type: Gastroenterology and hepatology

Country/Territory of origin: United States

Peer-review report's scientific

Kimberly PL Chong, College of Osteopathic Medicine, Western University of Health Sciences, Pomona, CA 91766, United States

Benjamin KP Woo, Department of Psychiatry and Biobehavioral Sciences, Olive View - University of California Los Angeles Medical Center, Sylmar, CA 91342, United States

Corresponding author: Benjamin KP Woo, MD, Associate Professor, Department of Psychiatry and Biobehavioral Sciences, Olive View - University of California Los Angeles Medical Center, 14445 Olive View Drive, Cottage H1, Sylmar, CA 91342, United States. bkpwoo@ucla.edu

Abstract

The field of gastroenterology has recently seen a surge in wearable technology to monitor physical activity, sleep quality, pain, and even gut activity. The past decade has seen the emergence of wearable devices including Fitbit, Apple Watch, AbStats, and ingestible sensors. In this review, we discuss current and future devices designed to measure sweat biomarkers, steps taken, sleep efficiency, gastric electrical activity, stomach pH, and intestinal contents. We also summarize several clinical studies to better understand wearable devices so that we may assess their potential benefit in improving healthcare while also weighing the challenges that must be addressed.

Key Words: Wearable technology; Wearables; Ingestibles; Smartphone; Remote patient monitoring; Gastroenterology

Core Tip: Wearable technology allows continuous health monitoring to provide a novel means of diagnosing and managing patients. Applications of wearable technology such as wrist wearables, abdominal wearables, smartphones and mobile apps, and ingestible sensors, are developing in gastroenterology. The aim of this review is to investigate current data from the literature that studies recent wearable technologies in several gastrointestinal diseases including inflammatory bowel disease, irritable bowel syndrome, and other functional gastrointestinal disorders.
INTRODUCTION

Wearable devices are revolutionizing medicine and impacting healthcare by enabling continuous health monitoring outside of the clinic\(^1\). These wearables include devices that can be worn from head to toe and even swallowed. In patients with gastrointestinal diseases such as inflammatory bowel disease and irritable bowel syndrome, these devices collect physical activity, sleep quality, heart rate and rhythm, and more recently, gut activity and gas profiles. Despite the surge of consumer interest in these technologies, there is a lack of sufficient evidence to support their widespread use in clinical practice.

The field of gastroenterology has seen an emergence of wearable technology that has the potential to diagnose, manage, and even prevent disease. As technological advancements continue, classifying devices into categories will become essential. The purpose of this article is to offer focused insights into backgrounds for categorizing devices, the various uses of wearable technology, and future opportunities for clinical applications, with a focus on wrist wearables, abdominal wearables, smartphones, and ingestible sensors (Table 1).

In this review, we performed a PubMed search using the search terms “wearables,” “wrist wearables,” “abdominal wearables,” “smartphones,” and “ingestible sensors.” We only selected manuscripts, which were original articles, and includes studies in several gastrointestinal diseases including inflammatory bowel disease, irritable bowel syndrome, and other functional gastrointestinal disorders. The objectives of this review were (1) to assess how wearable technology could assist physicians in investigating, diagnosing, or even treating our patients with gastrointestinal diseases; and (2) to recommend how wearable technologies could be applied in the future for several gastrointestinal diseases, including inflammatory bowel disease, irritable bowel syndrome, and other functional gastrointestinal disorders.

WEARABLE DATA TYPES AND USE

Wearable technology may be better understood by categorizing the types of data that can be collected. One type is data collection that requires active patient engagement with the device to obtain data that then can be transmitted in real time or uploaded to a stored source. This allows the user’s data to be collected by a device such as a wrist wearable, which then can be uploaded to the electronic health record. For example, active patient engagement may be used to correlate certain symptoms of acute mesenteric ischemia with electrocardiographic assessment to detect the presence of a related arrhythmia. Another type is data collection that does not require active initiation other than the first step of wearing the device. Once the device is worn, it may passively collect data by continuously or intermittently obtaining data to be transmitted or stored and later uploaded. These passive data collections may include continuous measurements of heart rate, respiratory rate, tone of voice, caloric intake, and gastrointestinal activity in a patient with an underlying gastrointestinal condition.

Wearable data may be most useful in its ability to inform individuals and physicians of the effects of the patient’s actions, management, or clinical status\(^2\). Ideally, these devices will provide data to offer decision support and even offer built-in therapies\(^3\). For example, we know that diet can be modified to modulate the microbiome\(^4\) but to effectively design individualized diets, feedback is needed to close the loop between a prescription and its effects. This feedback can offer automated recommendations for instant modification of a patient’s behavior and therapy. Even for devices that are unable to offer built-in therapy, the data collected can be used for diagnosis, prognosis, management, or prevention.
Table 1 Summary of wearable technology along with clinical applications

| Ref. | Device name | Device type | Clinical applications |
|------|-------------|-------------|-----------------------|
| [5,6,30,31] | Fitbit; Apple Watch; Amazon Halo | Wrist Wearable | Daily activity monitoring (steps taken, energy expenditure, and sleep hygiene) |
| [11] | Sweatssenser | Wrist Wearable | Inflammatory bowel disease monitor and management |
| [27,28] | Electrogastrogram | Abdominal Wearable | Ambulatory monitoring, functional GI disorders screening, diagnosis, and management |
| [31,32,34] | AbStats; G-Tech Medical | Abdominal Wearable | Bowel sounds and movement monitoring, postoperative ileus and delayed gastric emptying |
| [25] | N/A | Smartphone App | Meal logs, exercise, bowel movement, and sleep synchronized to electrogastrogram recording |
| [29] | UCLA eIBD patient app | Smartphone App | Inflammatory bowel disease activity monitor |
| [40] | HealthPROMISE app | Smartphone App | Tracks symptoms, quality of life, follow up, and intervention integrated with electronic health record |
| [41,42] | StudentLife app | Smartphone App | Assess stress, sleep, activity, mood, mental well-being, and academic performance |
| [43] | PoopMD; Pooplog | Smartphone App | Records stool types, records bowel movements |
| [44] | N/A | Ingestible | Vital sign monitor, motility disorder diagnosis and management |
| [45] | IMBED | Ingestible | Gastrointestinal bleed diagnosis, management, and monitoring |
| [46] | N/A | Ingestible | Understand intestinal function, microbiota, and individual response to dietary change |
| [54] | Colon Capsule Endoscopy | Ingestible | Minimally invasive colonoscopy method |
| [55] | Digital Pills | Ingestible | Monitor medication adherence |

IBD: Inflammatory bowel disease; UCLA: University of California Los Angeles; GI: Gastrointestinal; N/A: Not applicable.

WRIST WEARABLE DEVICES, INFLAMMATORY BOWEL DISEASE AND IRRITABLE BOWEL SYNDROME

Commercially available wrist wearable devices have grown rapidly in popularity during these recent years due to advancements in technology and the public’s increased health consciousness. These wrist wearable devices such as Fitbit, Apple Watch, and the new Amazon Halo aim to provide the user with real-time feedback on various aspects of daily activities such as number of steps taken, energy expenditure, sleep hygiene, and time spent in different levels of activity. They also provide personal goal setting options, data summary, and visualizations through synchronization with mobile- and computer-based apps such as health and fitness apps as well as options to connect to social media. Increasing consumer interest and improvement of data collecting capabilities of wearable technology has drawn attention to the devices as a potential avenue to improve the care of patients with inflammatory bowel disease (IBD) and irritable bowel syndrome (IBS).

IBD, which includes Crohn’s disease and ulcerative colitis, is characterized by chronic relapsing intestinal inflammation. Although the etiology of IBD remains largely unknown, it is thought that IBD results from an abnormal and continuing immune response to the microbes in the gut, catalyzed by the genetic susceptibility of the individual. Despite advances in therapeutic development, only 40%–60% of IBD patients can achieve remission at 1 year, and symptomatic relapse still occurs in at least 15% of patients per year. Prediction of symptomatic relapse would be highly desirable in IBD patients as this would allow for early intervention or prevention. Studies have shown that quality of life for individuals with IBD was poorer than for healthy individuals, for both adults and children. Effective and convenient strategies for prediction and prevention of relapse are needed.

IBD represents a chronic disease where the application of wearable technology may be able to improve management and predict or even prevent inflammatory disease flare. In a first study, Jagannath et al. used EnLaSense’s Sweatssenser for noninvasive continuous monitoring of interleukin-1 (IL-1β) and C-reactive protein (CRP), two key biomarkers associated with IBD, in human eccrine sweat. The sensor device demonstrated capability to detect and real-time monitor IL-1β and CRP in sweat. This study signifies a promising non-invasive wearable microsensor device that has the
potential to empower patients to actively engage in monitoring and managing their IBD. This device may also give patients the chance to intervene earlier and help gastroenterologists understand whether treatment is effective.

Wiestler et al.\cite{1} investigated the association of quality of life with wearable-based physical activity in patients with IBD. A total of 91 patients with IBD were evaluated in terms of disease-specific quality of life, using the Inflammatory Bowel Disease Questionnaire (IBDQ), and physical activity, using an accelerometer. The IBDQ was significantly lower in patients with moderate-severe disease activity as compared to patients in remission, and the physical activity level was higher in remission than in active disease. This study found that parameters of physical activity were significantly correlated with the IBDQ, and steps per day, vigorous activity, and sleep efficiency were significantly associated with the IBDQ. Importantly, the data positively correlate with health-related quality of life and demonstrates the positive effect of physical activity for patients with IBD.

Hirten et al.\cite{2} surveyed 400 patients with self-reported IBD and found that 89% of them believed that wearable devices can provide important information about their health, and 93.8% reported that they would use a wearable device if it could help their physician manage their IBD. The patients specifically identified wrist wearables as the preferred device type and reported a willingness to wear them at least daily. Because of patients’ willingness to participate, wearables allow them to actively engage in their health and further strengthen physician-patient collaboration, which will ultimately improve patient well-being and medicine as a whole.

Irritable bowel syndrome, one of the most common disorders of gut-brain interaction worldwide, is a functional disorder of the gastrointestinal tract characterized by chronic abdominal pain or discomfort and bowel habit changes in the form of diarrhea, constipation, or alternating patterns between the two\cite{3,4}. IBS is estimated to affect around 1 in 10 people globally\cite{5} and is associated with reduced quality of life\cite{6}.

Many studies have shown that increased physical activity has positive long-term effects on IBS symptoms and psychological symptoms\cite{7,8,9}. Hamaguchi et al.\cite{10} investigated the relationship between physical activity and gastrointestinal (GI) symptoms in 101 university students with IBS using the Gastrointestinal Symptoms Rating Scale and a pedometer, which measured gait steps for 1 wk. They found that the probability for daily locomotor activity to discriminate between 5 and 4 points on the Gastrointestinal Symptoms Rating Scale (i.e. likely to have reverse symptoms) decreased in accordance with increment of steps per day: 78% probability for 4000 steps, 70% probability for 6000 steps, 59% probability for 8000 steps, and 48% probability for 10000 steps. This study demonstrated that improvement in IBS symptoms increases with number of steps taken per day in IBS patients.

GI symptoms can also be triggered by several lifestyle factors including psychological distress, short sleep duration, and diet. Clevers et al.\cite{11} investigated the associations between selected lifestyle factors, measures of stress physiology, and GI symptoms. 1002 office employees were asked to report their GI symptoms, psychological distress, sleep times, and intake of caffeine, alcohol, and soft drinks for 5 d. They also recorded skin conductance, heart rate/variability, and acceleration using wearable sensors. Although the physiological variables such as skin conductance and heart rate variability were weakly associated with GI symptoms in this study, they found that short sleep duration was associated with next day GI symptoms and psychological distress mediated the association between short sleep duration and next day GI symptoms (61%).

Stress has been shown to play a major role in the onset and exacerbation of symptoms in IBS patients with stress related disorders such as anxiety and depression either preceding or following the development of IBS\cite{12}. With wearables’ capability of monitoring sleep, heart rate, physical activity, and tone of voice, these devices can alert patients of their well-being in real time and potentially recommend therapies to improve their well-being to serve as biofeedback to better control their stress and general health.

**ABDOMINAL WEARABLE DEVICES, FUNCTIONAL GASTROINTESTINAL DISORDERS AND POSTOPERATIVE USE**

The electrogastrogram (EGG) is a non-invasive device that is used for abdominal surface measurement of the gastric electrical activity of the human stomach\cite{13}. However, it is rarely used due to inconsistent results and signal artifacts that make
Functional GI disorders can affect any part of the GI tract including the esophagus, stomach, and intestines. They are disorders of function, rather than structural or biochemical abnormalities. Examples of functional GI disorders include functional dyspepsia, gastroparesis, and irritable bowel syndrome (IBS). Functional dyspepsia\cite{28}, which is characterized by a sensation of pain or burning in the epigastrium, early satiety, fullness during or after a meal, or a combination of these symptoms, has a global prevalence between 5\% and 11\%\cite{29}. Gastroparesis, which is characterized by delayed gastric emptying in the absence of mechanical obstruction, affects 4\% of the United States population\cite{30}. IBS, as stated above, is characterized by chronic abdominal pain and bowel habit changes, which deeply impairs and affects quality of life of many IBS patients. Functional GI disorders are typically diagnosed with subjective symptom-based assessment or objective but invasive procedures such as antroduodenal manometry, a procedure that measures motility with a catheter inserted through the mouth or nose with fluoroscopic or endoscopic guidance\cite{31}.

Gharibans et al\cite{27} developed an innovative device that overcame the technical issues of the EGG with a wearable multi-channel system and artifact removal signal processing method, making it comparable to antroduodenal manometry, the gold standard diagnostic method. This non-invasive and easily administered approach potentially allows for patient monitoring outside of the clinic, helps better understand functional GI disorders, and leads to more effective screening, diagnosis, and management. Gharibans et al\cite{27} also developed a smartphone app to enable the patients to document events or activities such as logging meals, exercise, bowel movement, and sleep, that are time-synchronized to the EGG recording for real-time feedback to the users.

The gut-brain axis consists of bidirectional communication between the central and the enteric nervous system, connecting emotional and cognitive centers of the brain with peripheral intestinal functions\cite{28}. IBS is an example of the disruption of these complex relationships. Vujic et al\cite{32} investigated the potential of using GI activity as an index of insula activity, which is the part of the brain associated with cognitive and affective functions. 33 participants with no known GI, neurological, or psychiatric disorders were connected to an EEG and EGG, presented emotionally salient film clips, and answered a self-assessment at the end of each clip. Although positive movie segments did not produce statistically significant changes ($P = 0.4706$), EGG signal analysis in the frequency domain demonstrated statistically significant changes from negative movie segments ($P = 0.0209$). Because EGG signals may be a sign of negative emotions, this gut-brain axis should be further studied in IBS patients in hopes of potential use of EGG in diagnosing and managing IBS.

Despite advances in surgical techniques, most patients develop temporary GI paralysis such as postoperative ileus (POI) and delayed gastric emptying (DGE) following abdominal surgery\cite{29}. When prolonged or complicated, POI can worsen patient outcomes, increase resource utilization and cost, and extend hospital length of stay by 30\%\cite{33}. Data reveal that continuous audio recordings of bowel sounds strongly correlate with true intestinal motility as measured using antroduodenal manometry\cite{34}. Spiegel et al\cite{35} developed an acoustic gastro-intestinal surveillance (AGIS) biosensor – the Gastrointestinal Logic AbStats system - a disposable plastic device embedded with a microphone that adheres to the abdominal wall and allows continuous and automated analysis of bowel sounds \emph{via} noninvasive vibration and sound sensing. They compared intestinal rates using AGIS in 8 healthy controls, 7 patients tolerating feeding, and 25 with POI. Mean intestinal rates were 0.14, 0.03, and 0.016 events per second, respectively. AGIS separated patients from controls with 100\% sensitivity and 97\% specificity.

DGE following pancreaticoduodenectomy (PD) is a common complication, which occurs in up to 30\% of cases\cite{36}. In primary DGE, which is when not associated with other risk factors or intra-abdominal complications, it is difficult to predict early on who will develop DGE after PD\cite{37}. Dua et al\cite{38} assessed whether the use of a novel, noninvasive wireless patch system (G-Tech Medical) that acquire gastric myoelectrical signals and transmit data by Bluetooth after PD is reproducible and can serve as an objective tool to identify patients who may be at risk of developing DGE. They found that tolerance of food was noted by 6 vs 9 d in the early versus late group by diet tolerance ($P < 0.05$) with higher cumulative gastric myoelectrical activity. Diminished gastric myoelectrical activity identified delayed tolerance to regular diet. This study introduces an abdominal wearable, wireless patch system capable of accurately monitoring gastric myoelectrical activity after surgery, which can not only objectively...
identify patients at risk for DGE but also potentially individualize feeding regimens to improve outcomes.

**SMARTPHONES AND REMOTE PATIENT MONITORING OF GASTROINTESTINAL DISORDERS**

The most common wearable device is the smartphone. The number of smartphone users has increased dramatically with smartphone ownership reported to be 43% globally and 72% in the United States[35]. Digital health refers to the use of digital, mobile, and wireless technologies to support achievement of health objectives, and the term is often interchangeably used with mobile health (mHealth) due to mobile devices’ central role[36]. Due to its increasing popularity, smartphones provide one of the most promising platforms for mHealth interventions including activity trackers, telemedicine capabilities, and health-based apps. The integration of smartphones and mobile apps, remote sensor technologies like Fitbit, telemedicine, and electronic health records (EHR) allows for remote patient monitoring (RPM), which refers to digital tools capable of monitoring and reporting real-time data on patients’ health activities outside of the usual healthcare settings[37,38].

Chronic GI disorders such as IBD and functional GI disorders are especially appropriate for RPM. Symptom flare risk and interventions required to control disease is heavily influenced by the patient’s behaviors, which occurs outside of the healthcare setting and often are not adequately tracked or assessed such as stress levels, depression, smoking, or medication adherence. Because of these factors, patients with chronic GI disorders are ideal candidates for RPM to potentially improve self-management, quality of life, and collaboration.

Van Deen et al[39] developed an mHealth index that accurately monitors IBD activity using patient reported outcomes, which is currently implemented in the University of California at Los Angeles eIBD patient app and automated messages are sent to a nurse coordinator when the mHealth index indicates disease activity.

Atreja et al[40] created the HealthPROMISE app, a cloud-based patient reported outcome and decision support platform, which helps patients track their symptoms, quality of life, follow up, and interventions in real time and provides point of care intervention from physicians by integrating the app with EHR.

Wang et al[41,42] used the StudentLife app, a continuous sensing app that uses the smartphone’s GPS, accelerometer, light sensor, and microphone integrated with call history, application usage, and texting patterns, to assess stress, sleep, activity, mood, sociability, mental well-being, and academic performance in college students. They found that the students’ depression was significantly negatively correlated with sleep and conversation frequency and duration. These smartphone apps plus the new Amazon Halo, which captures mood using microphone, also have the potential to be integrated with EHR to monitor for depression and anxiety.

Franciscovich et al[43] used PoopMD, a mobile app that utilizes a smartphone’s camera and color recognition software to analyze an infant’s stool, and determined a sensitivity of 100% and specificity of 89%. They found that PoopMD accurately differentiates acholic from normal color stool and may be a valuable tool to help parents identify acholic stool and alert the infants’ pediatricians. Apps like PoopMD and Pooplog, which allows patients to record bowel movements using the Bristol Stool Scale, can be further developed to be used in adult patients to identify various stools such as hematochezia and melena and even alert physicians of a possible GI bleed, infection, IBD flare, or constipation.

Studies have also shown that smartphones are widely used for social media and that a majority of social media is accessed through smartphones as compared to computers[44]. These social media such as Facebook, Instagram, and YouTube may have the potential to be used as platforms to broaden health education and outreach to a wider audience especially minority populations with cultural barriers to healthcare[45-47].

**INGESTIBLES, GASTROINTESTINAL HEALTH AND BEYOND**

Ingestible sensors, which are also known as swallowables, consist of a miniaturized detector and transmitter packed into a capsule that is swallowed and tracked through the intestine. Ingestibles are fast emerging with efforts continuously being made to
optimize these sensors for various clinical applications. These ingestible devices are noninvasive and provide information on pH, manometric pressure, temperature, medication adherence, vital signs, and intestinal lumen contents\(^5\).

Dagdeviren \textit{et al}\(^5\) developed an ingestible sensor that settles on the stomach lining and allows for monitoring of vital signs and mechanical deformation of the gastric cavity. This flexible ingestible piezoelectric device allows for possibilities in sensing mechanical variations and energy inside the GI tract, which may be applied in diagnosing and treating motility disorders and monitoring ingestion in obesity.

**Ingestibles and microbiome**

Mimee \textit{et al}\(^4\) created an ingestible micro-bio-electronic device that combines engineered probiotic sensor bacteria with microelectronics that communicates with an external device such as a smartphone. In this study, they engineered heme-sensitive probiotic biosensors and demonstrated accurate diagnosis of GI bleeds in swine (sensitivity and specificity of 83.3% at 60 min and 100% at 120 min). Thus, ingestible micro-bio-electronic device could transform diagnosis, management, and monitoring of GI health and disease.

The human gut is home to diverse microbes that play a fundamental role in the health and well-being of the host. The microbiota, which consists of bacteria, viruses, and eukaryotes, have been shown to interact with an individual's immune system to influence the development of diseases such as obesity, mental health issues, and atopic disease\(^5\). Gases of the gut, such as hydrogen carbon dioxide, nitrogen, and oxygen, have been significant in understanding the pathogenesis and diagnosis of gut disorders\(^5\). Gas production from bacterial fermentation is likely to produce symptoms in patients with diseases like IBS\(^5\) and small intestine bacterial overgrowth\(^5\). Kalantar-Zadeh \textit{et al}\(^4\) developed an ingestible electronic capsule that can sense oxygen, hydrogen, and carbon dioxide. This study showed the potential of this gas-sensing capsule in understanding functional aspects of the intestine, the microbiota, and intestinal response to dietary changes. This allows for a novel diagnostic and monitoring tool that can be used for various clinical indications such as constipation and obesity and can aid in development of individualized diets and lead to more personalized medicine.

**Colon cancer screening with ingestibles**

Although conventional colonoscopy is currently the gold standard for bowel cancer screening, the colon capsule endoscopy (CCE) continues to be further developed and improved since its introduction in 2007\(^4\). The currently available second generation CCE has been developed to look at the inside of the gut wall using visible light and two video cameras that cover nearly 360 degrees and transmits images to an external monitor\(^5\). This is used primarily for incomplete colonoscopy, polyp detection, and IBD, but with further technological advancements and research, CCE has the potential to be a minimally invasive and reliable method for bowel cancer screening.

**Ingestibles in medication monitoring**

Medication nonadherence is a common issue in healthcare, which may lead to poor outcomes in many patients. Digital pills are an innovative drug-device technology that combines medications with a monitoring system that records in real-time medication adherence\(^5\). An ingestible event marker is embedded within tablets and activated in the stomach. Once activated, the ingestible event marker communicates to a patch, which is applied to the patient’s torso, then the signal transmits \textit{via} Bluetooth to an external device such as a smartphone or computer. These digital pills allow physicians to monitor adherence among patients in hopes of improving rates of adherence and can further remote patient monitoring.

**DISCUSSION**

Wearable technology could represent a vital method for gastroenterologists to diagnose, manage, and monitor patients with numerous GI conditions and may even prevent disease. Because of the many available technologies such as remote sensor wearables, smartphones and mobile apps, telemedicine, and electronic health records, remote patient monitoring is very promising in the near future. Wearable devices have the ability to connect wirelessly to other devices, allowing the transfer and exchange of information and placing these devices in a category of technology known as the Internet-of-Things\(^5\). The Internet-of-Things is one framework that will make such a
future possible by providing the framework for exchange and communication of data between sensors and health care providers\textsuperscript{[58]}. This will benefit physicians and patients as wearable sensor systems can help reduce the costs associated with high-quality and continuous health care monitoring by reducing unnecessary hospital admission and length of stay\textsuperscript{[59]}, facilitate health behavior in the long run by monitoring and sending alerts to patients to give cues to modify behavior\textsuperscript{[60]}, and improve health in vulnerable populations\textsuperscript{[61]}.

Although wearable technology is a promising innovation in the field of gastroenterology, their use has also raised a number of concerns such as data accuracy and privacy issues (Table 2). Future studies could continue to investigate data accuracy of these various wearable technology as further developed and improved hardware and software algorithms are necessary before its use in daily clinical practice. Wearable devices store large amounts of information that is accessed by third parties, which creates a potential exposure of personal information to unauthorized users. Technological developments need to be carefully addressed to ensure that patients feel comfortable sharing a significant amount of data regarding their daily lives with health care providers, insurance companies, and data analytic companies\textsuperscript{[62]}. Regulations will also need to evolve continuously to ensure the best interest of the general population. Nonetheless, wearable technology continues to expand and make great impacts in patients’ lives from fitness to health and wellness monitoring to possible future diagnostic and management tools.

**CONCLUSION**

In general, remote patient monitoring in the field of gastroenterology are showing great promise for detection of GI conditions and managing and monitoring patients during their routine daily lives. They also show potential of reducing health care costs by encouraging better self-management and intervention approaches while allowing for a stronger physician patient collaboration and more personalized medicine. With rapidly advancing technological advancements, wearable technology has the potential to revolutionize how physicians provide high quality, reliable, and affordable health care to all.
Table 2 Benefits, challenges, and future advances of wearable technology

| Benefits | Challenges | Future research |
|----------|------------|-----------------|
| Method of diagnosis, management, monitoring, and prevention of various gastrointestinal conditions; Remote patient monitoring; Reduce healthcare costs; Encourage better patient self-management and intervention; Improve health in vulnerable populations; Reduce spread of disease and protective tool costs; Encourage better patient self-management and intervention; Improve gastrointestinal conditions; Remote patient monitoring; Reduce healthcare | Data inaccuracy; Privacy issues | Investigate data accuracy with improved hardware and software algorithms; Technological developments to ensure patient privacy; Regulations to ensure patient comfort with sharing data |

REFERENCES

1. Kim J, Campbell AS, de Avila BE, Wang J. Wearable biosensors for healthcare monitoring. Nat Biotechnol 2019; 37: 389-406 [PMID: 30804534 DOI: 10.1038/s41587-019-0045-y]
2. Kane JM. Technology-based interventions in health care. Epidemiol Psychiatr Sci 2014; 23: 323-326 [PMID: 25154596 DOI: 10.1017/S2045796014000444]
3. Vettoretti M, Cappon G, Acciaroli G, Facchinetti A, Sparacino G. Continuous Glucose Monitoring: Current Use in Diabetes Management and Possible Future Applications. J Diabetes Sci Technol 2018; 12: 1064-1071 [PMID: 29783897 DOI: 10.1177/193229681774078]
4. Johnson AJ, Vangay P, Al-Ghalith GA, Hillmann BM, Ward TL, Shields-Cutler RR, Kim AD, Shmagel AK, Syed AN; Personalized Microbiome Class Students, Walter J, Menon R, Koecher K, Knights D. Daily Sampling Reveals Personalized Diet-Microbiome Associations in Humans. Cell Host Microbe 2019; 25: 789-802. e5 [PMID: 31194939 DOI: 10.1016/j.chom.2019.05.005]
5. Chong KPL, Guo JZ, Deng X, Woo BKP. Consumer Perceptions of Wearable Technology Devices: Retrospective Review and Analysis. JMIR Mhealth Uhealth 2020; 8: e17544 [PMID: 32310148 DOI: 10.2196/17544]
6. Zhang YZ, Li YY. Inflammatory bowel disease: pathogenesis. World J Gastroenterol 2014; 20: 91-99 [PMID: 24415861 DOI: 10.3748/wjg.v20.i1.91]
7. Peyrin-Biroulet L, Lémann M. Review article: remission rates achievable by current therapies for inflammatory bowel disease. Aliment Pharmacol Ther 2011; 33: 870-879 [PMID: 21326896 DOI: 10.1111/j.1365-2656.2011.09299.x]
8. Bolge SC, Waters H, Piech CT. Self-reported frequency and severity of disease flares, disease perception, and flare treatments in patients with ulcerative colitis: results of a national internet-based survey. Clin Ther 2010; 32: 238-245 [PMID: 20206781 DOI: 10.1016/j.clinthera.2010.02.010]
9. Lönnsfors S, Vermeire S, Greco M, Hommes D, Bell C, Avedano L. IBD and health-related quality of life -- discovering the true impact. J Crohns Colitis 2014; 8: 1281-1286 [PMID: 24662394 DOI: 10.1016/j.crohns.2014.03.005]
10. Schirbel A, Reichert A, Roll S, Baumgart DC, Bünning C, Witig B, Wiedenmann B, Dignass A, Sturm A. Impact of pain on health-related quality of life in patients with inflammatory bowel disease. World J Gastroenterol 2010; 16: 3168-3177 [PMID: 20593502 DOI: 10.3748/wjg.v16.i25.3168]
11. Jaganath B, Lin KC, Pali M, Sankhala D, Muthukumar S, Prasad S. A Sweat-based Wearable Enabling Technology for Real-time Monitoring of IL-1β and CRP as Potential Markers for Inflammatory Bowel Disease. Inflamm Bowel Dis 2020, 26: 1533-1542 [PMID: 32720974 DOI: 10.1093/ibd/izu191]
12. Wiestler M, Kockelmann F, Kück M, Kerling A, Tegtbur U, Manns MP, Attaran-Bandarabadi M, Bachmann O. Quality of Life Is Associated With Wearable-Based Physical Activity in Patients With Inflammatory Bowel Disease: A Prospective, Observational Study. Clin Transl Gastroenterol 2019; 10: e0094 [PMID: 31770137 DOI: 10.14309/ctg.0000000000000094]
13. Hirten RP, Stanley S, Danieletto M, Borman Z, Grinspan A, Rao P, Sauk J, Chang L. Wearable Devices Are Well Accepted by Patients in the Study and Management of Inflammatory Bowel Disease: A Survey Study. Dig Dis Sci 2020 [PMID: 32705439 DOI: 10.1007/s10620-020-06493-y]
14. Linedale EC, Andrews JM. Diagnosis and management of irritable bowel syndrome: a guide for the generalist. Med J Aust 2017; 207: 309-315 [PMID: 28954618 DOI: 10.5694/mja17.00547]
15. Chang JY, Almazur AE, Richard Locke G 3rd, Larson JJ, Atkinson EJ, Talley NJ, Saito YA. Quantifying Rome symptoms for diagnosis of the irritable bowel syndrome. Neurogastroenterol Motil 2018; 30: e13356 [PMID: 29701271 DOI: 10.1111/nmo.13356]
16. Black CJ, Ford AC. Global burden of irritable bowel syndrome: trends, predictions and risk factors. Nat Rev Gastroenterol Hepatol 2020; 17: 473-486 [PMID: 32296140 DOI: 10.1038/s41575-020-02368-9]
17. Addante R, Naliboff B, Shih W, Presson AP, Tillisch K, Mayer EA, Chang L. Predictors of Health-related Quality of Life in Irritable Bowel Syndrome Patients Compared With Healthy Individuals. J Clin Gastroenterol 2019; 53: e142-e149 [PMID: 29351154 DOI: 10.1097/MCG.0000000000000978]
18. Johansson E, Ringström G, Abrahamsson H, Sadik R. Intervention to increase physical activity in irritable bowel syndrome shows long-term positive effects. World J Gastroenterol 2015; 21: 600-608 [PMID: 25593485 DOI: 10.3748/wjg.v21.i2.600]
Chong KPL et al. Wearable technology applications in gastroenterology

19 Hajizadeh Maleki B, Tarrabian B, Moorien FC, FitzGerald LZ, Krüger K, Chehrazi M, Malandish A. Low-to-moderate intensity aerobic exercise training modulates irritable bowel syndrome through antioxidative and inflammatory mechanisms in women: Results of a randomized controlled trial. *Cytokine* 2018; 102: 18-25 [PMID: 29274540 DOI: 10.1016/j.cytob.2017.12.016]

20 Hamaguchi T, Tayama J, Suzuki M, Nakaya N, Takizawa H, Koizumi K, Amano Y, Kazazawa M, Fukado S. The effects of locomotor activity on gastrointestinal symptoms of irritable bowel syndrome among younger people: An observational study. *PloS One* 2020; 15: e0234089 [PMID: 32470988 DOI: 10.1371/journal.pone.0234089]

21 Clevers E, Lutin E, Cornelis J, Van Oudenhove L. Gastrointestinal symptoms in office workers are predicted by psychological distress and short sleep duration. *J Psychosom Res* 2020; 138: 110230 [PMID: 32927308 DOI: 10.1016/j.jpsychores.2020.110230]

22 O’Mahony SM, Clarke G, Dinan TG, Cryan JF. Irritable Bowel Syndrome and Stress-Related Psychiatric Co-morbidities: Focus on Early Life Stress. *Handb Exp Pharmacol* 2017; 239: 219-246 [PMID: 28233180 DOI: 10.1007/164_2016_128]

23 Al Kafee A, Akan A. Analysis of gastric myoelectrical activity from the electro gastrogastrogram signals based on wavelet transform and line length feature. *Proc Inst Mech Eng H* 2018; 232: 403-411 [PMID: 29441814 DOI: 10.1177/0954411918757812]

24 Talley NJ, Ford AC. Functional Dyspepsia. *N Engl J Med* 2015; 373: 1853-1863 [PMID: 26535514 DOI: 10.1056/NEJMra1510505]

25 Ford AC, Marwaha A, Sood R, Moayyedi P. Global prevalence of, and risk factors for, uninvestigated dyspepsia: a meta-analysis. *Gut* 2015; 64: 1049-1057 [PMID: 25147201 DOI: 10.1136/gutjnl-2014-307842]

26 Aibel TL, Bernstein RK, Cutts T, Farrugia G, Forster J, Hasler WL, McCallum RW, Olden KW, Parkman HP, Parrish CR, Pasricha PJ, Prather CM, Soffer EE, Twillman R, Vinik A. Treatment of gastroparesis: a multidisciplinary clinical review. *Neurogastroenterol Motil* 2006; 18: 263-283 [PMID: 16553582 DOI: 10.1111/j.1365-2982.2006.00760.x]

27 Ghazibahns AA, Smarr BL, Kunkel DC, Kriegsfeld LJ, Mousa HM, Coleman TP. Artifact Rejection Methodology Enables Continuous, Noninvasive Measurement of Gastric Myoelectric Activity in Ambulatory Subjects. *Sci Rep* 2018; 8: 5019 [PMID: 29568042 DOI: 10.1038/s41598-018-23302-9]

28 Vujic A, Krause C, Tso G, Lin J, Han B, Maes P. Gut-Brain Computer Interfacing (GBCI): Wearable Monitoring of Gastric Myoelectric Activity. *Annu Int Conf IEEE Eng Med Biol Soc* 2019; 2019: 5886-5889 [PMID: 31947189 DOI: 10.1109/EMBC.2019.8856568]

29 Doorly MG, Senagore AJ. Pathogenesis and clinical and economic consequences of postoperative ileus. *Surg Clin North Am* 2012; 92: 259-272, viii [PMID: 22444412 DOI: 10.1016/j.suc.2012.01.010]

30 Ageirsson T, El-Badawi KI, Mahmood A, Barletta J, Luchtefeld M, Senagore AJ. Postoperative ileus: it costs more than you expect. *Surg Clin North Am* 2012; 92: 259-272, viii [PMID: 22444412 DOI: 10.1016/j.suc.2012.01.010]

31 Tomomasa T, Morikawa A, Sandler RH, Mamsy HA, Koneko H, Masahiko T, Hyman PE, Itzh O. Gastrointestinal sounds and migrating motor complex in fasted humans. *J Am Coll Surg* 2010; 210: 228-231 [PMID: 20139444 DOI: 10.1016/j.jamcollsurg.2009.09.028]

32 Spiegel BM, Kaneshiro M, Russell MM, Lin A, Patel A, Tashjian VC, Zegarski V, Singh D, Cohen SE, Reid MW, Whitman CB, Talley J, Martinez BM, Kaiser W. Validation of an acoustic gastrointestinal surveillance biosensor for postoperative ileus. *J Gastrointest Surg* 2014; 18: 1795-1803 [PMID: 25091837 DOI: 10.1007/s11605-014-2597-y]

33 Atema JJ, Eshuis WJ, Busch OR, van Gulik TM, Gouma DJ. Association of preoperative symptoms of gastric outlet obstruction with delayed gastric emptying after pancreatoduodenectomy. *Surgery* 2013; 154: 583-588 [PMID: 23972659 DOI: 10.1016/j.surg.2013.04.006]

34 Dua MM, Navalgund A, Axelrod S, Axelrod L, Worth PJ, Norton JA, Poultsides GA, Triadafilopoulos G, Visser BC. Monitoring gastric myoelectric activity after pancreaticoduodenectomy for diet “readiness”. *Am J Physiol Gastrointest Liver Physiol* 2018; 315: G743-G751 [PMID: 30048596 DOI: 10.1152/ajpgi.00074.2018]

35 Poushier J. Smartphone Ownership and Internet Usage Continues to Climb in Emerging Economies But Advanced Economies Still Have Higher Rates of Technology Use. Washington, DC: Pew Research Center; 2016

36 World Health Organization. Monitoring and evaluating digital health interventions: A practical guide to conducting research and assessment. In: Sexual and reproductive health, 2016 [cited 20 February 2021]. Available from: https://www.who.int/reproductivehealth/publications/dighealth/digital-health-interventions/en/

37 Atreja A, Otobo E, Ramireddy K, Deorocki A. Remote Patient Monitoring in IBD: Current State and Future Directions. *Curr Gastroenterol Rep* 2018; 20: 6 [PMID: 29516186 DOI: 10.1007/s11894-018-0611-3]

38 Treskses RW, van der Veldt EB, Barendse R, Bruining N. Mobile health in cardiology: a review of electromagnetic signals based on wavelet transform and line length feature. *Proc Inst Mech Eng H* 2018; 232: 403-411 [PMID: 29441814 DOI: 10.1177/0954411918757812]

39 Van Deen WK, van der Meulen-de Jong AE, Otobo E, Ramireddy K, Deorocki A. Remote Patient Monitoring in IBD: Current State and Future Directions. *Curr Gastroenterol Rep* 2018; 20: 6 [PMID: 29516186 DOI: 10.1007/s11894-018-0611-3]
Atreja A, Khan S, Rogers JD, Outoe B, Patel NP, Ullman T, Colombel JF, Moore S, Sands BE; HealthPROMISE Consortium Group. Impact of the Mobile HealthPROMISE Platform on the Quality of Care and Quality of Life in Patients With Inflammatory Bowel Disease: Study Protocol of a Pragmatic Randomized Controlled Trial. JMIR Res Protoc 2015; 4: e23 [PMID: 25093610 DOI: 10.2196/resprot.4042]

Wang R, Chen F, Chen Z, Li T, Harari G, Tignor S, Zhou X, Ben-Zeav D, Campbell AT. StudentLife: Assessing mental health, academic performance and behavioral trends of college students using smartphones [cited 20 February 2021]. In Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing, Seattle, WA, USA, 2014: 3-14

DaSilva AW, Hucksins JF, Wang R, Wang W, Wagner DB, Campbell AT. Correlates of Stress in the College Environment Uncovered by the Application of Penalized Generalized Estimating Equations to Mobile Sensing Data. JMIR Mhealth Uhealth 2019; 7: e12084 [PMID: 30888327 DOI: 10.2196/12084]

Francisco-ovich A, Vaidya D, Doyle J, Bolinger J, Capdevila M, Rice M, Hancock L, Mahr T, Mogul DB. PoopMD, a Mobile Health Application, Accurately Identifies Infant Acholic Stools. PLoS One 2015; 10: e0132207 [PMID: 26221719 DOI: 10.1371/journal.pone.0132207]

Guo JZ, Chong KPL, Woo BKP. Utilizing YouTube as platform for psychiatric emergency patient outreach in Chinese Americans. Asian J Psychiatr 2020, 50: 101960 [PMID: 32086173 DOI: 10.1016/j.ajp.2020.101960]

Shu S, Woo BKP. Digital Media as a Proponent for Healthy Aging in the Older Chinese American Population: Longitudinal Analysis. JMIR Aging 2020; 3: e20321 [PMID: 32543447 DOI: 10.2196/20321]

Dunn PH, Woo BKP. Facebook recruitment of Chinese-speaking participants for hypertension education. J Am Soc Hypertens 2018; 12: 690-692 [PMID: 30054194 DOI: 10.1016/j.jash.2018.06.017]

Lam NHT, Woo BKP. Efficacy of Instagram in Promoting Psychoeducation in the Chinese-Speaking Population. Health Equity 2020; 4: 114-116 [PMID: 32258963 DOI: 10.1089/heq.2019.0078]

Dagdeviren C, Javid F, Joe P, von Erlach T, Bensel T, Wei Z, Saxton S, Cleveland C, Booth L, McDonnell S, Collins J, Hayward A, Langer R, Traverso G. Flexible piezoelectric devices for gastrointestinal motility sensing. Nat Biomed Eng 2017; 1: 807-817 [PMID: 31015594 DOI: 10.1038/s41551-017-0140-7]

Mimee M, Nadeau P, Hayward A, Carim S, Flanagan S, Jerger L, Collins J, McDonnell S, Swartwout R, Citorik RJ, Bulové V, Langer R, Traverso G, Chandrakasan AP, La TK. An ingestible bacterial-electronic system to monitor gastrointestinal health. Science 2018; 360: 915-918 [PMID: 29798884 DOI: 10.1126/science.aaq3155]

Clemente JC, Ursell LK, Parfrey LW, Knight R. The impact of the gut microbiota on human health: an integrative view. Cell 2012; 148: 1258-1270 [PMID: 22424233 DOI: 10.1016/j.cell.2012.01.035]

Mathur R, Amichai M, Chua KS, Mirocha J, Barlow GM, Pimentel M. Methane and hydrogen positivity on breath test is associated with greater body mass index and body fat. J Clin Endocrinol Metab 2013; 98: E698-E702 [PMID: 23532244 DOI: 10.1210/jc.2012-3144]

Major G, Pritchard S, Murray K, Alappadan JP, Hoad CL, Marciani L, Gowland P, Spiller R. Colon hypersensitivity to Distension, Rather Than Excessive Gas Production, Produces Carbohydrate-Related Symptoms in Individuals With Irritable Bowel Syndrome. Gastroenterology 2017; 152: 124-133. e2 [PMID: 27746233 DOI: 10.1053/j.gastro.2016.09.062]

Shin W. Medical applications of breath hydrogen measurements. Anal Bioanal Chem 2014; 406: 3931-3939 [PMID: 24848162 DOI: 10.1007/s00216-013-7606-6]

Kalantar-Zadeh K, Berean KJ, Ha N, Chimes AF, Xu K, Grando D, Ou JZ, Pillai N, Campbell JL, Briklača R, Taylor KM, Burgell RE, Yao CK, Ward SA, McSweeney CS, Muir JG, Gibson PR. A human pilot trial of ingestible electronic capsules capable of sensing different gases in the gut. Nat Electron 2018; 1: 79-87 [DOI: 10.1038/s41928-017-0004-x]

Spada C, Riccioni ME, Petruzziello L, Marchese M, Urgesi R, Costamagna G. The new PillCam Colon capsule: difficult colonoscopy? Gastrointest Endosc 2008; 68: 807-810 [PMID: 18402958 DOI: 10.1016/j.gie.2008.01.030]

Yung DE, Rondonotti E, Koulouzoudis A. Review: capsule colonoscopy-a concise clinical overview of current status. Ann Transl Med 2016; 4: 398 [PMID: 27867950 DOI: 10.21037/atm.2016.10.71]

Kopelowicz A, Baker RA, Zhao C, Brewer C, Lawson E, Peters-Strickland T. A multicenter, open-label, pilot study evaluating the functionality of an integrated call center for a digital medicine system to optimize monitoring of adherence to oral aripiprazole in adult patients with serious mental illness. Neuropsychiatr Dis Treat 2017; 13: 2641-2651 [PMID: 29089771 DOI: 10.2147/NDT.S143091]

Cirillo F, Wu FJ, Solnaz M, Kovacs E. Embracing the Future Internet of Things. Sensors (Basel) 2019; 19 [PMID: 30654571 DOI: 10.3390/s19020351]

Mortara A, Pinna GD, Johnson P, Maestri R, Caponolla S, La Rovere MT, Ponikovskiy P, Tavazzi L, Sleigh P; HHH Investigators. Home telemonitoring in heart failure patients: the HHH study (Home or Hospital in Heart Failure). Eur J Heart Fail 2009; 11: 312-318 [PMID: 19228800 DOI: 10.1093/ejhf/hfp022]

Patel MS, Asch DA, Volpp KG. Wearable devices as facilitators, not drivers, of health behavior change. JAMA 2015; 313: 459-460 [PMID: 25569175 DOI: 10.1001/jama.2014.14781]

Levine J. The Application of Wearable Technologies to Improve Healthcare in the World’s Poorest
People. *Technology and Investment* 2017; 8: 83-95 [DOI: 10.4236/ti.2017.82007]

62 Dunn J, Runge R, Snyder M. Wearables and the medical revolution. *Per Med* 2018, 15: 429-448
[PMID: 30259801 DOI: 10.2217/pme-2018-0044]
