WJG World Journal of Gastroenterology

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World J Gastroenterol 2021 March 28; 27(12): 1149-1160

DOI: 10.3748/wjg.v27.i12.1149

ISSN 1007-9327 (print) ISSN 2219-2840 (online)

MINIREVIEWS

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

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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.

Manuscript source: Invited manuscript

Specialty type: Gastroenterology and hepatology

Country/Territory of origin: United States

Peer-review report's scientific

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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.

quality classification
Grade A (Excellent): 0
Grade B (Very good): 0
Grade C (Good): C
Grade D (Fair): 0
Grade E (Poor): 0

Received: December 9, 2020
Peer-review started: December 9, 2020
First decision: January 23, 2021
Revised: February 12, 2021
Accepted: March 10, 2021
Article in press: March 10, 2021
Published online: March 28, 2021

P-Reviewer: Torres MRF
S-Editor: Zhang L
L-Editor: A
P-Editor: Ma YJ

Citation: Chong KP, Woo BK. Emerging wearable technology applications in gastroenterology: A review of the literature. *World J Gastroenterol* 2021; 27(12): 1149-1160
URL: https://www.wjgnet.com/1007-9327/full/v27/i12/1149.htm
DOI: https://dx.doi.org/10.3748/wjg.v27.i12.1149

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 gastro-intestinal 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
[5,12,13,20,21]	Fitbit; Apple Watch; Amazon Halo	Wrist Wearable	Daily activity monitoring (steps taken, energy expenditure, and sleep hygiene)
[11]	Sweatsenser	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
[27]	N/A	Smartphone App	Meal logs, exercise, bowel movement, and sleep synchronized to electrogastrogram recording
[39]	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
[48]	N/A	Ingestible	Vital sign monitor, motility disorder diagnosis and management
[49]	IMBED	Ingestible	Gastrointestinal bleed diagnosis, management, and monitoring
[50]	N/A	Ingestible	Understand intestinal function, microbiota, and individual response to dietary change
[56]	Colon Capsule Endoscopy	Ingestible	Minimally invasive colonoscopy method
[57]	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[5]. 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[6]. 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[6]. 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[7,8]. 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[9,10]. 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*[11] used EnLiSense's Sweatsenser 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*[12] 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*[13] 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 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[14,15]. IBS is estimated to affect around 1 in 10 people globally[16] and is associated with reduced quality of life[17].

Many studies have shown that increased physical activity has positive long-term effects on IBS symptoms and psychological symptoms[18,19]. Hamaguchi *et al*[20] 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*[21] 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[22]. 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[23]. However, it is rarely used due to inconsistent results and signal artifacts that make interpretation and continuous monitoring difficult. Recent studies have shown the potential of EGG as an effective and non-stationary method to differentiate diabetic gastroparesis and functional dyspepsia patients[23].

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[24], 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%[25]. Gastroparesis, which is characterized by delayed gastric emptying in the absence of mechanical obstruction, affects 4% of the United States population[26]. 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[27].

Gharibans *et al*[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*[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[28]. IBS is an example of the disruption of these complex relationships. Vujic *et al*[28] 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 EGG and EEG, 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[29]. When prolonged or complicated, POI can worsen patient outcomes, increase resource utilization and cost, and extend hospital length of stay by 30%[30]. Data reveal that continuous audio recordings of bowel sounds strongly correlate with true intestinal motility as measured using antroduodenal manometry[31]. Spiegel *et al*[32] developed an acoustic gastro-intestinal surveillance (AGIS) biosensor – the Gastroinstestinal 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 *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[33]. In primary DGE, which is when not associated with other risk factors or intraabdominal complications, it is difficult to predict early on who will develop DGE after PD[34]. Dua *et al*[34] 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 myoelectric 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[48].

Dagdeviren *et al*[48] 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 pieozoelectric 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 *et al*[49] 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[50]. Gases of the gut, such as hydrogen carbon dioxide, nitrogen, and oxygen, have been significant in understanding the pathogenesis and diagnosis of gut disorders[51]. Gas production from bacterial fermentation is likely to produce symptoms in patients with diseases like IBS[52] and small intestine bacterial overgrowth[53]. Kalantar-Zadeh *et al*[54] 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[55]. 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[56]. 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[57]. 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 *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[58]. 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[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[59], facilitate health behavior in the long run by monitoring and sending alerts to patients to give cues to modify behavior[60], and improve health in vulnerable populations[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[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 for healthcare workers; Facilitate physician patient collaboration towards personalized medicine	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

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