MINIREVIEWS

Clinical application and research progress of extracellular slow wave recording in the gastrointestinal tract

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Abstract

The physiological function of the gastrointestinal (GI) tract is based on the slow wave generated and transmitted by the interstitial cells of Cajal. Extracellular myoelectric recording techniques are often used to record the characteristics and propagation of slow wave and analyze the models of slow wave transmission under physiological and pathological conditions to further explore the mechanism of GI dysfunction. This article reviews the application and research progress of electromyography, bioelectromagnetic technology, and high-resolution mapping in animal and clinical experiments, summarizes the clinical application of GI electrical stimulation therapy, and reviews the electrophysiological research in the biliary system.

Key Words: Gastrointestinal tract; Slow wave; Electromyography; High-resolution mapping; Bioelectromagnetic technology

Core Tip: The motility pattern of the gastrointestinal (GI) tract is fundamental in studying functional GI disorders. Extracellular recording has been used to characterize the generation and propagation of slow waves and abnormalities that may lead to GI motility disorders. This review focuses on the application and progress of extracellular recording techniques in the physiological and pathological state of the alimentary system.

INTRODUCTION

The gastrointestinal (GI) tract is a complex organ that efficiently processes nutrients and waste. These tasks are facilitated by the phasic contractions resulting from a cyclical depolarization-repolarization cycle, known as electrical slow waves. The slow wave potential of the GI tract is generated by interstitial cells of Cajal (ICCs) distributed in the submucosa and smooth muscle layer of the GI wall and spreads to smooth muscle cells (SMCs), causing excitation-contraction coupling[1]. SMCs and ICCs are also electrically coupled with platelet-derived growth factor receptor alpha-positive (PDGFRα+) cells, forming an integrated unit called the SMC-ICC-PDGFRα+ cells (SIP) syncytium[2,3]. SIP cells provide pacemaker activity, propagation pathways for slow waves, transduction of inputs from motor neurons, and mechanosensitivity[4,5].

Alvarez *et al*[6] and Berkson *et al*[7] first recorded the extracellular slow wave potential of the stomach and small intestine, and proved the consistency between the frequency of slow wave and the rhythm of GI contraction. Over the past century, extracellular electrical recording technology has become one of the most critical methods to characterize the generation and propagation of slow wave and GI motility disorders[8]. The milestone research of GI extracellular slow wave recording is provided in Table 1. The limitation of electromyography (EMG) is the lack of temporal-spatial features of slow wave propagation, which has been proved to be an essential indicator of GI dysfunction[9]. In recent years, research on high-resolution (HR) mapping of GI mucosal slow wave using array matrix electrodes *in vivo* and a bioelectromagnetic technique for recording the magnetic field produced by GI electrical activity, has provided more accurate and reliable support for research on the role of GI dysrhythmia in digestive diseases.

This review explores the application and progress of extracellular recording techniques in the physiological and pathological states of the alimentary system.

GI ELECTROPHYSIOLOGY

In the GI tract, SMCs form gap junctions with two types of interstitial cells, ICCs and PDGFRα+ cells, creating a highly integrated electrical SIP syncytium. Electrical coupling makes it very difficult to deduce the specific functions of one component in intact tissues, so the functions of SIP cells have benefitted from studies of particular cell types[10]. ICCs are organized into networks in the pacemaker regions of the GI tract[11]. Spontaneous electrical activity is generated by ICCs, which are electrically coupled to the SMCs[12,13]. Once a slow wave is generated, it regenerates and propagates actively through the ICC network. Depolarization of SMCs by slow wave enhances the open probability of L-type voltage-dependent calcium (Ca^{2+}) channels, resulting in the generation of Ca^{2+} action potentials, which are superimposed upon the peaks of slow waves. Slow waves are actively propagated in GI muscle tissues, enabling the recruitment of thousands of SMCs to contract together or in sequence to generate segmental and peristaltic contractions. In normal condition, the PDGFRα+ cells network runs parallel or even intercalates with that formed by the ICC network. PDGFRα+ cells express small conductance calcium-activated potassium channel 3 (SK3) channels and P2Y1 receptors[14,15]. These proteins are essential for the purinergic inhibitory regulation of GI motility[5,16,17]. GI motility patterns are highly integrated behaviors requiring coordination between SMCs and utilizing regulatory inputs from interstitial cells (ICCs and PDGFRα+ cells), neurons, and endocrine and immune cells[11,18].

Disorders of gastroduodenal function without an apparent organic cause, defined by the Rome IV criteria, are common, including functional dyspepsia, chronic nausea and vomiting, belching, and rumination disorders[19]. The resultant inefficiencies contribute to vast health and economic burden, considering societal prevalence rates of > 10% for functional dyspepsia and > 2% for chronic nausea and vomiting[20-22]. Diagnosing GI functional disorders remains challenging. Slow waves are omnipresent in GI organs, and motor activity is controlled, in part, by modulation of the frequency, amplitude, and

Table 1 Milestone research of extracellular gastrointestinal slow wave recording

Ref.	Year	Research type	Methods	Part of GI	Major advances
Alvarez *et al*[6]	1922	Rabbits	Monopolar electrode	Small intestine	First record the SW
Alvarez[32]	1922	Human	EGG	Abdominal wall	First electrogastrogram recording
Code and Marlett [89]	1974	Dogs	Multi-electrode	Stomach	First report gastric arrhythmia
Code *et al*[29]	1975	Dogs	Multi-electrode	Stomach and small intestine	Define the MMC
Hinder and Kell [54]	1977	Human	Multi-electrode	Stomach	First locate the gastric pacemaker
Di Luzio *et al*[90]	1989	Human	MGG	Stomach and small intestine	Noninvasively investigate the activity of the GI system
Miranda *et al*[91]	1992	Human	ACB	Stomach	Study stomach emptying model
Bradshaw *et al* [92]	2003	Rabbits	MGG	Stomach	Investigate gastric electrical activity under normal and vagotomized condition
Corá *et al*[76]	2005	Human	ACB	Stomach	Obtain a comprehensive knowledge of the behavior of pharmaceutical forms in the GI tract
Lammers *et al*[93]	2008	Dogs	HR mapping	Stomach	First observe the spatial origin and propagation patterns of SW arrhythmias
Bradshaw *et al* [68]	2009	Human	MGG	Stomach	Obtain spatiotemporal parameters of the gastric SW
Du *et al*[62]	2009	Pigs	HR mapping	Stomach	Design a new sterilized PCB electrode
O'Grady *et al*[66]	2009	Pigs and human	HR mapping	Stomach	Design a novel laparoscopic device for HR mapping
O'Grady *et al*[55]	2010	Human	HR mapping	Stomach	The most comprehensive study of the gastric conduction system
Farajidavar *et al* [52]	2012	Dogs	Multi-wireless modules	Stomach	Design a bidirectional wireless system for SW recording
Calabresi *et al*[72]	2015	Rats	ACB	Stomach	Assess gastric motility
Gharibans *et al* [94]	2017	Electrophysiology model	HR-EGG	Stomach	Address the spatial limitations of the EGG
Gharibans *et al* [95]	2019	Human	HR-EGG	Stomach	Achieve comprehensive spatial analytics of gastric far-field gastric potentials

ACB: Alternate current biosusceptometry; EGG: Electrogastrogram; GI: Gastrointestinal tract; HR: High-resolution; MGG: Magnetogastrogram; MMC: Migrating motor complex; PCB: Printed circuit board; SW: Slow wave.

duration of slow waves[23,24]. ICC loss and injury are now a significant research focus, as it is recognized as a hallmark of several functional GI motility disorders[25]. Hence, coupling between slow waves and contractions is vital in understanding GI motility and developing concepts about what might lead to motility disorders. It requires techniques to record and model the patterns of slow wave generation and propagation.

EMG

Since 1922, when Alvarez *et al*[6] first recorded the slow wave of an experimental animal using bioelectric recording devices, EMG has gradually developed into a technique for recording bioelectric signals produced by nerve-muscle activity, using electrical stimulation to detect nerve and muscle excitation conduction function, and has assisted in the diagnosis and treatment of diseases[26]. In the field of GI electrophysiology, the most commonly used electrodes are monopole electrodes and surface electrodes.

Monopolar electrode

The monopole electrode records the action potential (AP) of the muscle fiber adjacent to the electrode so that the signal of AP amplitude is reliable and prominent[27]. Szurszewski *et al*[28] investigated the

myoelectric activity of the small intestine in conscious healthy dogs by implanting a monopolar electrode in the muscular layer of the small intestine and found that the periodic AP activity spreads slowly from the duodenum to the end of the ileum. This regular electrical activity only occurs during fasting. In follow-up research, Code *et al*[29] divided the periodic GI myoelectric activity, namely, the migrating motor complex (MMC), into four typical stages (I-IV). Phase I is the quiescent phase with no contractions, phase II is characterized by random contractions, phase III has a sudden onset and ends with a burst of contractions with maximal amplitude and duration, and phase IV is characterized by the rapid decrease of contractions. The human GI tract also has regular MMCs, and is regulated by circadian rhythms, hormones, nerves, and other factors[24].

As monopolar electrode implantation is an invasive operation, the main complications are pain, bleeding, infection, and perforation[27,30,31]. Moreover, the reference electrode is routinely placed on the surface of the skin near the tested tissue or organ, so the recorded myoelectric signal has many interferences and poor baseline stability. Therefore, the monopolar electrode is rarely used in the clinical diagnosis and treatment of diseases of the digestive system.

Electrogastrography

Electrogastrography (EGG) is a non-invasive technique for recording GI myoelectric activity using a surface electrode placed on the abdominal wall[32]. Many early studies have shown a good correlation between EGG and EMG, which was recorded with a monopolar electrode[33,34]. Familonie *et al*[35] recorded the surface EGG and intragastric EMG of postoperative patients and healthy subjects, respectively. They found that EGG could not only detect normal slow wave and electrical rhythm but also successfully detected abnormal EGGs in patients with clinical GI symptoms.

EGG is currently regarded as an auxiliary diagnostic examination in the clinic, which is used to evaluate nausea, vomiting, and other GI rhythm disorders, eventually exploring the mechanism of functional GI disease[36,37]. Chen *et al*[38] found that approximately 75% of gastroparesis patients had preprandial or postprandial abnormal signal patterns following EGG examination of healthy subjects and gastroparesis patients. About 60% of patients with functional dyspepsia have an abnormal EGG, including delayed gastric emptying and slow wave reduction[39]. A prospective study that compared the EGG of mechanical, vascular, and paralytic intestinal obstruction, combined with inflammatory indices, indicated that EGG has a high sensitivity in evaluating vascular and paralytic intestinal obstruction, even though its specificity is low. However, the significant correlation between EGG and plasma levels of interleukin-6 and procalcitonin supports the role of inflammation in the pathogenesis of impaired gastric electrical activity in patients with intestinal obstruction[40].

EGG also shows potential in clinical pharmacological research, digestive system development, GI function evaluation, and treatment safety evaluation. A case-control study that studied the EGG changes in patients with esophageal variceal bleeding during treatment with octreotide found that octreotide could inhibit gastric electrical activity and was positively correlated with its hemostatic effect. Therefore, EGG can be used as a predictive index to evaluate the efficacy of octreotide in treating esophageal variceal bleeding[41]. Ortigoza *et al*[42] simultaneously used EGG, abdominal near-infrared spectroscopy, and intestinal tinnitus acoustics to monitor the development of the GI tract in premature infants, evaluate the safety of enteral feeding, and reduce the morbidity and mortality of premature infants.

Because the relative position of the electrode affixed to the body surface is easy to deviate from the stomach, it is difficult for the recording system to obtain stable and repeatable data. The main parameter of EGG analysis is the frequency of slow wave, which cannot fully reflect the function of the GI tract. Therefore, the value of EGG in clinical diagnosis is limited[43].

GI electrical stimulation

The GI myoelectric abnormalities observed in the models of gastroparesis, intractable nausea and vomiting, and intestinal obstruction provide a theoretical basis for the development of GI electrical stimulation (GIES) therapy[38,44]. According to the location of electrical stimulation, GIES can be divided into inhibitory electrical stimulation and excitatory electrical stimulation[45]. Inhibitory electrical stimulation can inhibit the contractile movement of the normal GI tract by placing the electrode near the tail end of the GI tract to send stimulation signals, forcing GI myoelectric activity and movement to reverse propagation[46,47]. Excitatory electrical stimulation, also known as "electrical pacing," promotes GI peristalsis by implanting electrodes into the area near the physiological pacemaker to send electrical stimulation signals[48,49].

Recently, many clinical studies have shown that GIES can improve the physiological function of the GI tract and relieve clinical symptoms by setting different parameters and electrical stimulation sites (Table 2). However, as a treatment modality, GIES is still in the exploratory stage. A meta-analysis based on case-control studies found that GIES had a significant "placebo effect" in the treatment of gastroparesis. Therefore, GIES therapy requires further clinical studies to prove its safety and efficacy and related animal models to explore the pathogenic mechanism[50]. Although GIES is still controversial, it has great potential to improve and treat GI motility disorders[51,52].

Table 2 Clinical research on gastrointestinal electrical stimulation

Ref.	Methods	Sample size	Indications	Location of GIES	Stimulation parameters	Duration	Results
Gastric electrical stimulation							
McCallum *et al*[96]	Multicenter, double-blind, RCT	32	Idiopathic gastroparesis	Stomach	14 Hz, 5 mA, 330 μs	3 mo	Significant decrease in vomiting and days of hospitalization
Teich *et al* [97]	Prospective study	16 (children)	Chronic nausea andvomiting	Stomach	14 Hz, 5 V, 330 μs	0.5-23 mo	Significant improvement in severity and frequency of vomiting, frequency, and severity of nausea
Morales-Conde *et al* [98]	Randomized, multicenter trial	47	Obesity	Stomach	/	24 mo	Limited weight regain with strong safety outcomes
Ducrotte *et al*[99]	RCT	172	Refractory vomiting	Stomach	14 Hz, 5 mA, 330 μs	8 mo	Effectively reduced the frequency of refractory vomiting in patients with and without diabetes, although it did not accelerate gastric emptying or increase the quality of life
Intestinal electrical stimulation							
Norton *et al* [100]	RCT	90	Fecal incontinence	Anus	35 Hz, 300 ms	8 wk	Improved bowel control to a modest extent
Daram *et al* [101]	Case report	1	Roux stasis syndrome	Jejunum	14 Hz, 5 mA, 330 μs	5 d	Effective relief of the symptom of stasis post-Roux-en-Y anastomosis
Cadeddu *et al*[102]	Randomized trial	81	Idiopathic constipation	Anus	2 Hz, 30-35V, 360-960 μs	6 times	Continuous improvement of constipation symptoms and anorectal function
Nerve electrical stimulation							
Fassov *et al* [103]	RCT	20	IBS	Sacral nerve	14 Hz, 0.1-4.0 V, 210 μs	3 wk	Reduced symptoms of diarrhea-predominant and mixed IBS
Stakenborg *et al*[104]	Pilot study	18	Post-colectomy surgery	Abdominal vagus nerve	5, 20 Hz, 2.5 mA, 0.5, 1, 2 ms	2 times (preparation, postoperation)	Inhibition of IL-6 and IL-8 induced by lipopolysaccharide to prevent postoperative intestinal obstruction
Zhang *et al* [105]	Pilot study	42	Major abdominal surgeries	Acupoints ST36 and PC6	25 Hz, 2-10 mA, 0.5 ms	3 d	Improved major postoperative symptoms
Teckentrup *et al*[106]	RCT	22	Healthy subjects	Vagus nerve	25 Hz, 0.3-0.9 mA	2 d	Reduced the frequency of gastric myoelectricity and did not affect resting energy consumption

GIES: Gastrointestinal electrical stimulation; IBS: Irritable bowel syndrome; IL: Interleukin; RCT: Randomized controlled trial.

HR MAPPING

In clinical practice, the myoelectric signal obtained directly from the surface of the GI tract is still the most reliable method for analyzing GI myoelectricity. However, both EMG and EGG are highly dependent on equipment hardware, filtering technology, and the size and material of recording electrodes. They could only obtain low-resolution GI myoelectric recordings, which have limited value for analyzing slow wave propagation mode and speed of the GI tract. By placing multiple arrays of electrodes on the serous surface of the GI tract to record GI myoelectric signals, HR mapping can accurately analyze GI myoelectric signals and electrical rhythm disorders under pathological conditions [53].

Gastric pacing region

Alvarez *et al*[6] first studied the pacing region of the human stomach and proposed the hypothesis that the "pacing region" may be located in the lesser curvature of the gastric cardia. Hinder *et al*[54] roughly located the "gastric pacing region" in the greater curvature of the middle gastric corpus by implanting multiple pairs of monopolar electrodes. Through HR mapping research of the stomach in patients with normal gastric function, O'Grady *et al*[55] found that the slow wave of the stomach originated from a "special region" in the middle and upper part of the great curvature of the stomach, which was consistent with the results of Hinder's work. They also found significant regional spread of slow waves from the pacing area to the distal gastric antrum. However, the pacing region lacked specialized

anatomical tissue or cellular structures and was labile in that if it was to be removed, a neighboring region would become the apparent site of initiation[56].

Gastric conduction system

HR mapping studies in humans and large animal healthy stomach models have shown that slow waves arise from the defined pacemaker region and are quickly propagated in a circular waveform from the pacing area to the antrum[55,57-59]. In the human stomach, the annular slow waves are propagated longitudinally at a velocity of 3 mm·s^{-1} until the distal antrum is continuously moving at a higher velocity (almost > 7 mm·s^{-1}) at the greater *vs* lesser curvature and eventually terminate in the pylorus [55]. Interestingly, slow waves do not normally excite the gastric fundus[60].

HR mapping technology has apparent advantages in diagnosing and treating GI motility disorders. In an HR mapping study, O'Grady *et al*[61] found that approximately 50% of experimental pigs with abnormal gastric function had abnormal rhythms, including incomplete and complete conduction block, escape rhythm competing, ectopic pacemakers, and functional re-entry. Subsequently, Du *et al*[62] designed and optimized a flexible printed circuit board that can be sterilized repeatedly, which can be used for HR mapping of the slow wave of the GI tract in an experimental animal model and shows excellent spatiotemporal accuracy, thus providing a low cost and stable alternative for clinical GI myoelectric detection. A recent clinical study comparing EGG and HR mapping showed that gastric slow waves exhibit pacing and conduction abnormalities in patients with gastroparesis, but their frequency is not significantly abnormal, resulting in the missed detection of abnormal gastric myoelectricity on the EGG, indicating that earlier studies likely underestimated both the prevalence and complexity of gastric dysrhythmia[63]. Berry *et al*[64] found that ectopic pacing of the remnant stomach after laparoscopic sleeve gastrectomy is one of the possible mechanisms leading to postoperative chronic gastric dyskinesia. Mapping studies also revealed how anisotropic propagation, re-entry, and conduction block contribute to motility disruption during dysrhythmia[61,63,65]. These works have enabled several novel clinically relevant insights into the features and mechanisms of gastric arrhythmias.

However, due to the limitations of invasive examination, HR mapping is rarely applied in the clinic. A clinical study attempted to detect and analyze the rhythm and propagation pattern of gastric slow wave reliably through trocars in the limited area of the gastric mucosa (limited by the number of trocars, usually less than four) during laparoscopic surgery[66]. Implanting temporary electrodes in the GI mucosa through the endoscope may be the direction of its future development.

BIOELECTROMAGNETIC TECHNOLOGY

Compared with EMG and HR mapping technology, bioelectromagnetic technology has the advantages of non-invasiveness, non-ionizing radiation, and low risk, which provides a new direction for the research of GI tract dynamics. Until now, the bioelectromagnetic techniques used in GI research are mainly based on the alternate current biosusceptometry (ACB) of tracking the movement of magnetic tracers in the GI tract after ingestion and magnetogastrography (MGG) to detect the magnetic field produced by the electrical activity of GI smooth muscle[67,68].

ACB

ACB is a bioelectromagnetic technique that records the changes in the magnetic flux of magnetic tracers ingested *in vivo* with the movement of the GI tract by placing induction coils and reference coils *in vitro*. This technique has the advantages of simplicity, easy operation, and low cost in investigating gastric emptying time and dynamic activity of the GI tract in humans or experimental animals[69]. An animal experiment studying the effect of triple immunosuppressive therapy on GI function found that both ACB and EGG can accurately monitor the contraction frequency and amplitude of the GI tract. Américo *et al*[70] implanted magnetic markers and monopole electrodes under the serosa of the distal stomach and proximal ascending colon in beagle dogs. Compared with EMG, these works proved that ACB could safely and effectively record the contractile activity of GI smooth muscle *in vitro*. The ACB image could visualize intrasegmental tracer distribution and the automated scan of the GI motility segments [71-73]. In two animal experiments, analysis of the relationship between ACB and the strain-gauge signal amplitude showed that ACB may serve as an accurate and sensitive technique for GI motility research[74,75].

In the field of pharmacological research, Corá *et al*[76] obtained a magnetic image of the disintegration of drug tablets in the human stomach using ACB, which shows that the ACB has sufficient sensitivity and spatial resolution in evaluating drug dosage forms *in vivo*. It provides a new research method for comprehensively understanding the metabolic model of drug dosage forms in the human GI tract and developing a new drug delivery system to improve and control the bioavailability and effectiveness of drugs. Another study developed a biomagnetic cellulose gel composed of polymeric nanocapsules containing ferrite nanoparticles, which can be substantially retained in the stomach walls, and consequently has the potential to be used as a traceable drug delivery system for gastric diseases

[77].

However, the measurement of ACB is easily affected by the magnetic tracer, the shape and position of the coils, and the spatial position of the tracer relative to the coils. Bruno *et al*[78] combined ultrasound and ACB to overcome its overdependence on the position and distribution of magnetic tracers in magnetic inductors. Above all, ACB has apparent advantages in recording gastric emptying, which reflects the unique superiority of ACB in GI function evaluation[79].

MGG

MGG is a bioelectromagnetic technique based on a superconducting quantum interferometer to detect the extracellular magnetic field produced by the slow wave of the GI tract, which is highly related to EGG[69]. Several studies have shown that MGG is less affected by the difference in electrical conductivity of the tissue, so it is easier to reflect the physiological characteristics of slow waves in the GI tract[68,69,80]. Based on a study of the effect of erythromycin on gastric motility, Somarajan *et al*[81] compared the differences among MGG, EGG, and EMG, proving that MGG could objectively indicate gastric dysrhythmia and quantify the therapeutic effect in patients with functional gastropathy. In addition, MGG can reliably detect spatial parameters such as propagation velocity and mode of GI slow wave. Recently, Bradshaw *et al*[82] measured EGG and MGG in seven healthy subjects and seven patients with diabetic gastroparesis. The parameters such as dominant frequency, percentage of power distribution, and propagation characteristics were compared. They found that MGG could detect the pathological slow wave of gastroparesis. Above all, MGG shows unique advantages in detecting transmission speed and propagation mode, which provides a new method for studying the pathological myoelectric characteristics of digestive diseases.

ELECTROPHYSIOLOGICAL RESEARCH ON THE GALLBLADDER AND BILIARY TRACT

Early studies on MMC have shown that rhythmic myoelectric activity also exists in the biliary system, which is regulated by many factors such as cholecystokinin, cholinergic receptor agonists, and intestinal peristalsis[83]. Romański *et al*[84] found that the minute rhythm occurs regularly in the entire ovine small intestine and gallbladder, which is controlled by nicotinic receptors and muscarinic receptor subtypes. In benign gallbladder diseases, research on biliary dysfunction, especially smooth muscle in the biliary tract and the sphincter of Oddi, is from animal experiments. Abell *et al*[85] designed an annular electrode to detect Oddi sphincter EMG without damaging the Oddi sphincter wall, which has the advantages of less trauma, convenient placement, accurate location, and high repeatability. In the guinea pig lithogenic model, EMG was used to detect the myoelectric difference in the Oddi sphincter at different stages under a high cholesterol diet, indicating that Oddi sphincter dysfunction caused by a high cholesterol diet may be one of the pathogenic mechanisms of cholesterol gallstones[86]. Liu *et al*[87] also found Oddi sphincter dysfunction in rabbits with chronic cholangitis and proved that the intracellular calcium mobilization pathway was involved in the relaxation of the sphincter under pathological conditions.

To date, there is still little research on gallbladder myoelectricity. It may be because of the weak gallbladder myoelectricity or signal close to the heart or respiration, making it difficult for researchers to obtain stable myoelectric signals. Therefore, the gallbladder myoelectric activity detection method needs to be continuously optimized and improved. Recently, we detected gallbladder EMG in guinea pigs with acute acalculous cholecystitis (AAC) using a bipolar electrode, which showed that the slow wave frequency in the control group was 10.66 ± 0.51 cpm, in the AAC 12 h group was 7.13 ± 0.20 cpm (mean ± standard deviation; $P < 0.001$), in the AAC 24 h group was 6.46 ± 0.16 cpm, and in the AAC 48 h group was 5.75 ± 0.43 cpm (unpublished data). There was no significant difference among the AAC 12 h, AAC 24 h, and AAC 48 h groups. This suggests that inflammation may first affect the function of gallbladder ICCs, then decrease gallbladder slow wave frequency, and eventually lead to a decline in gallbladder function.

With a deeper understanding of the electrophysiology of the biliary system, clinicians have begun to re-examine the necessity of gallbladder function evaluation for benign gallbladder diseases. Currently, the primary methods for evaluating gallbladder function are gallbladder angiography, three-dimensional ultrasonic detection, cholescintigraphy, and Oddi sphincter manometry, which indirectly evaluate gallbladder function through parameters such as gallbladder emptying and biliary pressure [88]. There is still a lack of direct methods to evaluate biliary function in the clinic. The advantages of EMG, bioelectromagnetic technology, and HR mapping in the study of the physiological function of the GI tract provide a new research direction for the evaluation of biliary system function, especially for gallbladder function. We believe that gallbladder EMG is the most concise, reliable, and direct method for evaluating gallbladder function. However, there is still a lack of research on gallbladder EMG under physiological and pathological conditions. Compared with EMG, HR mapping can directly detect the myoelectricity of the gallbladder and provide a spatiotemporal model of the origin and propagation pattern of gallbladder myoelectricity. This will enable a more comprehensive understanding of the origin and spread of myoelectric activity in gallbladder pathophysiology and may provide new

evaluation methods for the diagnosis and treatment of benign gallbladder diseases. Nevertheless, because EMG and HR mapping are invasive examinations, non-invasive low-risk bioelectromagnetic technology may be the best method for clinical gallbladder function evaluation in the future.

CONCLUSION

The rhythmic slow wave in the GI tract is the basis for the realization of the physiological function of the digestive system. EMG detects the GI electrical signals by placing electrodes on the GI serosa or mucosal surface and has been widely used to study the normal physiological rhythm of the GI tract and the mode of dyskinesia under pathological conditions. Because EMG is an invasive technique, which limits its application in clinical diagnosis and treatment, it is mainly used in clinical scientific research and electrical stimulation therapy. Therefore, non-invasive detection technologies such as EGG and bioelectromagnetic technology are gaining more and more attention from scientific researchers and clinical workers. EGG collects GI electrical signals through the surface electrode of the abdominal wall, but it is easily affected by the difference in tissue conductivity. ACB and MGG, which are based on bioelectromagnetic technology, could not only accurately record the frequency and distribution of GI slow wave, but also provide their time-space variation parameters. HR mapping is also an invasive technique for detecting GI myoelectric signals. Unlike EMG, HR mapping uses array electrodes to obtain the myoelectric signal of the GI serosa surface, which can accurately obtain the spatial propagation model. Given the lack of electrophysiological research on the gallbladder, it will be an important research direction in the field of GI electrophysiology in the future.

FOOTNOTES

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