Quantification of Dynamic Gastric Slow Wave Activity using Recurrence Plots

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Abstract—The genesis and maintenance of abnormal or dysrhythmic bio-electrical slow wave activity in the gut is poorly understood. The use of multi-electrode densely spaced electrodes to map in-vivo slow wave activity from the stomach surface provides a renewed understanding of gastric electrophysiology in health and disease. Analysis of the experimental data thus far have typically only utilized linear methods. Nonlinear methods such as the use of recurrence plots could provide key insights into physiological mechanisms. In this paper we applied recurrence analysis to synthetic propagation and experimental data, in cases where the activity was normal, abnormal and transitional. The recurrence plots were quantified using recurrence rate (RR) and diagonal length entropy (DLE). Normal activity had a higher mean RR than dysrhythmic and transition cases (0.08±0.01 vs 0.03±0.01 and 0.03±0.01). Transition cases had a lower mean RR than dysrhythmic and normal activity (2.16±0.23 vs 3.30±0.58 and 3.01±0.42). The use of recurrence analysis in the gastrointestinal field will allow for a better understanding of normal activity, as well as provide insights into the mechanisms that are involved in initiation, maintaining and terminating dysrhythmic slow wave activity. It could also be used as a novel qualitative and quantitative approach to predict the progression of slow wave activity.

I. INTRODUCTION

Bio-electrical myogenic slow waves are generated and propagated by interstitial cells of Cajal (ICC) in the gastric musculature [1]. They are responsible for coordinating gastric motility [2]. In the human stomach, slow waves occur around three cycles per minute (cpm), and initiates around the greater curvature of the upper corpus and propagates distally towards the antrum. The slow wave conduction system has a higher velocity at the pacemaker region, at 8 mm/s, and then travels around the corpus region at 3 mm/s, and then increases speed at the antrum to a rate of 6 mm/s [3]. These characteristics allow for up to three propagating wavefronts to be simultaneously present in the stomach. Loss of ICC is a significant contributor towards functional motility disorders, such as gastroparesis, and has been associated with abnormal or dysrhythmic slow wave activity [4], [5].

High-resolution (HR) in-vivo electrical mapping of slow waves provides a detailed spatio-temporal view of the propagation profiles and can allow for in-depth investigation into electrophysiological mechanisms that drive dysrhythmias. Generally, HR mapping analysis involves the detection of the activation phase of slow waves and grouping these events into propagating wavefronts, followed by velocity and amplitude quantification [6]. This is a time-intensive task and novel ways to process, analyse and visualise the data are required to analyze physiological mechanisms.

In other biological fields, the use of recurrence analysis has been utilized to provide key insights into how physiological and disease states progress over time. The use of recurrence plot (RP) was first introduced by Eckmann et al. [7] to investigate time dependent behavior of complex dynamical systems in phase space. Since then it has been used in other fields to investigate various biological processes. Webber and Zbilut [8] used RP analysis to discern between quiet and active breathing in laboratory rats, while Kałużny and Tarnecki used recurrence to study neuronal spike trains in cats [9]. In the cardia field RPs have been used to predict the termination of atrial fibrillation using surface electrocardiograms [10].

In this study we introduce the use of recurrence analysis in gastric HR slow wave mapping. The method was validated using synthetic datasets after-which it was applied to in-vivo experimental data to illustrate its efficacy and ability to detect changes in spatio-temporal propagation profiles.

II. MATERIALS & METHODS

A. Synthetic Data

To validate recurrence quantification, synthetic propagation patterns at 3 cpm were generated as previously described [11]. In brief, for a 10 x 10 electrode array with 4 mm spacing, linear activation wavefronts were simulated for 200 s. Then elliptical wavefronts representing a pacemaker was simulated for a further 200 s, followed by colliding wavefronts for another 200 s. Colliding wavefronts represent the presence of two pacemakers, illustrating a change to the system dynamics. Synthetic noise was added as normally distributed noise (0.5±0.5 s) to represent activation timing error and experimental noise.

B. Experimental Methods

Ethical approval for experimental in-vivo recordings in pigs was granted by the University of Auckland Ethics Committee. HR serosal slow wave gastric recordings were performed in five pigs (36.2±3.7 kgs). The surgical and monitoring methods used to acquire the data were performed as previously described [12]. In brief, the animals were anesthetized, after which a mid-line laparotomy was performed.
to gain access to the gastric serosa. Flexible printed circuit electrodes (up to 256 recordings sites at 4 mm resolution) were then placed on the gastric serosa and packed with warm saline gauze prior to recording. The data was recorded at 512 Hz using an ActiveTwo (Biosemi, The Netherlands) data acquisition system modified for passive recordings, with the reference lead placed on the left hind-leg thigh of the pig.

C. Recurrence plots

The HR signals were filtered using a moving median filter to remove baseline wander and a Savitzky-Golay filter to remove high-frequency noise [13]. The activation times were then detected using automated and manual marking methods [6].

To create a RP, first the activation times in the signal were transformed into a phase signal (-π to π) as shown in Fig. 1 [14]. The 1D phase signals were then mapped into a 2D activation time (AT) phase map according to the 2D electrode arrangement. Fig. 2 shows six AT phase maps, where the first AT phase map is used as the reference map. The reference map was quantitatively compared to all other AT phase maps (i.e., Fig. 2 A to Fig. 2 B-F) using the absolute median difference (AMD) between AT phase maps. If the AMD was below a defined threshold, the compared AT phase map was considered to a recurrent pattern and at that time point it was denoted as 1 in the recurrence plot (RP) time matrix.

The RP matrix has two dimensions where both are time, and describes if there is similar information in one time when compared to all other time in the recording. A threshold of AMD less than 0.3 was determined from testing synthetic data to represent recurrence. For computational efficiency, the phase signals were sampled at 6 Hz.

To quantify the RPs, two metrics were computed (i) Recurrence rate (RR) and (ii) Diagonal line entropy (DLE). RR is a measure of the density of the recurrent points in the RP time matrix, and is defined as,

\[ RR = \frac{1}{N^2} \sum_{i,j=1}^{N} RP_{ij} \]  

where N is the length of the recording. RR typically ranges from 0 to 1, where a high RR illustrates a high degree of recurrence in the RP and vice versa.

DLE is the Shannon entropy of the distribution of the diagonal line length in the RP and is defined as,

\[ DLE = - \sum_{l=l_{\text{min}}}^{N} P(l) \ln(P(l)) \]  

where \( P(l) \) is the histogram of diagonal lines with length \( l \), and \( l_{\text{min}} = 2 \), is the minimum number of points for a diagonal line. DLE represents the complexity of deterministic structures in the system and acts to denote if the RP is homogeneous (high DLE) or irregular (low DLE).

III. RESULTS

The synthetic data was simulated using three different propagation patterns. Fig. 3 shows the RP being able to discern the change in propagation profile across time. RP was quantified for the three patterns and while the patterns were changing from one state to another. RR and DLE was higher during stable activity than transitory state (RR: 0.07±0.01 vs 0.03±0.01, DLE: 2.8±0.2 vs 2.0±0.01).

RPs were constructed for five experimental data sets with a median recording time of 8 minutes per dataset. RP plots were able to illustrate subtle changes from one state to another. Fig. 4 shows the RP of an experimental data set where there was normal antegrade wavefront for 4 min, followed by a sequence of events, where there was a small patch of secondary ectopic pacemaker. Current classification algorithms may be unable to detect these change in patterns [6], [15].

All experimental and synthetic data were manually classed into ‘Normal’, ‘Dysrhythmic’ and ‘Transition’. Normal wavefronts displayed stable patterns with a stable frequency, while dysrhythmic wavefronts exhibited erratic periodicity and changing wavefront patterns. Transition periods were identified when the pattern of activity switched from one pattern to another. Fig. 5 shows the relationship between the
three classes of activity. Normal cases had a higher mean \( RR \) than dysrhythmic and transition cases (0.08±0.01 vs 0.03±0.01 and 0.03±0.01). Transition cases had a lower mean \( DLE \) than dysrhythmic and normal cases (2.16±0.23 vs 3.30±0.58 and 3.01±0.42).

A significant computational cost of this method is the comparison of AT phase maps to determine if there is recurrence. With a larger data set, the time-cost increases quadratically (\( O(n^2) \)). For a 3 minute HR recording it takes up 5 seconds to compute the RP time matrix, while for a 12 minute HR recording it takes up to 3 minutes of computational time.

### IV. DISCUSSION

In this study we introduced the use of recurrence analysis for gastrointestinal (GI) HR slow wave mapping data. The use of RPs allows for qualitative and quantitative estimation of the dynamical state of the gastric slow wave conduction system. The methods were tested with synthetic data after which they were applied to in-vivo experimental data sets.

Recurrence analysis is a non-linear method that allows the study of complex periodic and chaotic systems. Time series data are generally time lagged according to Taken’s embedding theorem which creates multi-dimensional data allowing for phase space and recurrence analysis [16], [17]. With the use of densely populated multi-electrode slow wave data, propagational characteristics were investigated rather than single channel data. Thus, we employed the technique.
used by Van Hunnik et al. [14] where they converted cardiac multi-electrode signals to a phase map for recurrence comparison.

This is the first known exploratory use of recurrence analysis in the GI HR mapping field. Initial results demonstrate the quantification of RP illustrates a delineation between the normal, dysrhythmic and transitory states. The recurrence rate was high between normal and dysrhythmic states, whilst it was low during transitory state, where the propagation patterns were switching. Normal slow wave activity had higher entropy in the RP than dysrhythmic and transitory states of the slow wave conduction system. In this study we focused on the study of in-vivo slow wave activation phase. Translation of this method to the recovery phase of slow waves may yield additional insight into the mechanisms that drive the initiation and maintenance of slow wave dysrhythmias [18].

The main advantage of RPs is that it does not require partitioning of the data into propagating wavefronts, which is usually manually driven and leads to bias. The use of RP could also assist in automating the clustering of propagating wavefronts. RPs also provide a novel approach for qualitative assessment of slow wave data rather than using isochronal mapping. One of the key indicators in electrophysiology is the assessment of whether conduction patterns are stable or chaotic; and recurrence analysis is able to provide this information in a reliable manner. This technique could also be used as an effective tool to isolate regions of interest in the gut for novel therapies such as pacing and ablation. Furthermore, it could also be used to assess the stability of slow wave with the intake of prokinetics or other drugs to treat functional motility disorders.

This analysis of stable wavefront has provided significant insight into the mechanisms of cardiac arrhythmias and similar principles apply in the GI field, but thus far have not been investigated. The use of this technique could also be extended to HR mapping in the intestine and colon, but will require further validation and verification analysis. The method is also applicable to a relatively few number of channels and can be extended to cutaneous recordings.

V. CONCLUSIONS

In conclusion, we have introduced the use of recurrence analysis to GI mapping. This techniques has the ability to capture the stability and dynamics of the slow wave conduction system in a reliable manner.

REFERENCES


