NGM Technical Note

Anatomical registration and three-dimensional visualization of high-resolution pan-colonic manometry recordings

Running Title
Anatomical mapping for colonic manometry

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Abstract

A novel three dimensional technique to visualize complex manometric data has been developed. This technique enables data to be displayed in a manner that is more intuitive, as the original context of the data is preserved. The characterization of normal and abnormal colonic motility patterns, as well as further sub-classification of dysmotility, can be enhanced using this data gathering and visualization technique.

Keywords: colon, constipation, three dimensional visualization, manometry, fibre-optic.
Introduction

Constipation is a common and distressing condition that conveys a major socioeconomic burden as well as individual suffering\(^1\),\(^2\). Disregulated colonic contractile activity is implicated in constipation\(^3\),\(^4\) yet quantitative data that unequivocally differentiates normal from abnormal colonic function is lacking\(^5\). This is likely due to several technical and analytical barriers that prevent the accurate manometric profiling of colonic luminal pressure patterns.

Since 1988, colonic manometric studies have utilised catheters with \(\leq 16\) sensors spaced at \(\geq 5\)cm intervals\(^6\),\(^7\). While these data have provided some insight into the dysmotility associated with constipation they simply cannot provide the detail that is currently achieved with high-resolution (HR) manometry in other regions of the digestive tract, such as the oesophagus\(^8\). To overcome this we have recently developed and utilised a novel high-resolution fibre-optic manometry catheter that has the capability for recording motility data at 1cm intervals throughout the entire colon\(^9\).

Whilst HR colonic manometry offers the potential to gain substantial new insights into normal and abnormal colonic motility, it also brings major analytical challenges. Colonic manometry recordings are generally taken over hours or days, yielding a vast data set. Key data features must be extracted and distilled in an efficient analysis pipeline, and communicated via intuitive visualization methods that allow for rapid identification of general or regional abnormalities\(^4\). Moreover, whilst we have previously developed a technique of spatiotemporal mapping colonic propagating pressure waves\(^10\), that technique is limited to displaying data from a single subject. Displaying grouped mean data of pressure wave regional frequency or amplitude still relies on graphs, which become excessively complex with HR recordings.

This study introduces novel solutions for current analysis needs in both low and high resolution colonic manometry, enabling the anatomical registration and visualization of colonic manometry data, via a three dimensional (3D) virtual model.
Methods

Patients and controls:

Presented data were obtained from two previously published sources; i) 24-hr pan-colonic water perfused manometry in 8 healthy controls and 14 patients with slow transit constipation (16 sensors at 7.5 cm resolution) \(^4\); ii) 24-hr fibre-optic high resolution pan-colonic recordings in a patient with slow transit constipation (72 sensors at 1 cm resolution) \(^9\). In both studies, the manometry catheters were endoclipped to the caecum/ascending colon mucosa at colonoscopy. Protocols for water perfused and fibre-optic manometric recordings have been described in detail elsewhere \(^4,9\).

Data Extraction

Propagating pressure waves were indentified in a semi automated fashion using custom software, developed at the St. George clinical school and written in Matlab (The MathWorks, MA, US) and Java (Sun Microsystems, CA, USA). Definitions of propagating sequences and propagating pressure waves have been defined previously \(^11\); Briefly a PS consisted of an array of 3 or more PPWs recorded in adjacent sites.

Anatomical Registration and Visualization

The 3D model framework employed in this study was translated from methods described earlier by Fernandez et al \(^12\). In brief, a 3D data cloud was created by digitizing the surface of the human colon using serial slices of the visible human data set \(^13\). A 3D finite element surface was then fitted to the data cloud, using a least squares minimization technique \(^12\). Fixed anatomical reference points were identified at the caecum, hepatic and splenic flexures, the descending-sigmoid colon junction, and the anus.

For the water perfused studies, the colon was divided into 16 regions (region 1 = cecum, region 4 = hepatic flexure, region 8 = splenic flexure, region 12 = proximal sigmoid colon, region 16 = rectum) \(^11\). Recording sideholes were assigned to the colonic region within which they lay, with sidehole 1 always in region 1 as it was clipped to the cecum \(^4\). For the fibre-optic studies, a plain abdominal x-ray with the catheter in situ was taken (Figure 2E), from which all recording sensors were identified and assigned an anatomical site according to their specific colonic locations.
Manometry data from the above anatomical sites was translated to the corresponding points on the geometric mesh. The remaining data between each of the fixed neighboring points was linearly interpolated along the centre line of the virtual colon. This data manipulation was achieved using scripts written in the PERL programming language, and the data were visualized using CMGUI, a software platform developed at the University of Auckland. This technique ensured that the displayed pressure at anatomical points of interest was preserved when transferred from the patient data to the model. The interpolated pressures were then projected from the center line of the colon onto the three-dimensional walls of the virtual colon.

For this paper we have included the cumulative frequency and amplitude of the antegrade propagating pressure waves per colonic region. These data have been recently been published in another format previously\(^4,9\). A white-blue spectrum was used to visualize the propagating pressure wave cumulative frequency data over the 3D model, where white indicates no pressure waves and dark blue indicates the highest frequency of propagating pressure waves. The average amplitude of propagating pressure waves per colonic regions are shown using a white-red spectrum.

**Comparison to Alternative Methods**

Data from individual patients and controls have been displayed as spatiotemporal maps and standard histograms as presented previously\(^4\).

**Results**

By way of example, spatiotemporal maps of a healthy control and a patient with slow transit constipation are presented (Fig 1A). These allow visualisation of propagating sequence data for individual subjects and help to highlight abnormal motility in patients (Figure 1A)\(^4\). However they cannot be used to display grouped mean data, which are presented as histograms. These can be unintuitive with multisensor data (Figure 1B) and become prohibitively complex with HR data (72 sensors). Histograms can be simplified by binning data into anatomical regions (eg. ascending, transverse, descending colon), however that defeats the purpose of recording data with multiple sensors.
Alternatively, grouped mean data can be displayed on 3D colonic images (Fig 2 A, B, C & D). These 3D images clearly communicate characteristics we have previously described in the colon of patients with slow transit constipation; e.g. a lack of high amplitude pressure (Figure 2(B)) and a characteristic paucity of propagating pressure waves in the distal transverse and splenic flexure (Figure 2(D)) \(^4\).

Importantly, the novel techniques developed here can then be applied to HR data sets. Here we have displayed data from a single patient. Figure 2(E) shows the fiber-optic catheter positioned in the colon of a female patient with slow transit constipation. The cumulative frequency of the propagating pressure waves recorded at each sensor over a 24 hour period is then interpolated on Figure 2(F). In this patient the figure clearly indicates propagating pressure waves recorded in the transverse and sigmoid colon with a marked reduction of activity throughout the entire descending colon.


Discussion

This study presents novel approaches to anatomically registering and presenting pan-colonic manometry data, allowing 3D visualization of key results. This ‘pipeline’ of methods represents a substantially more intuitive way of displaying colonic intraluminal pressures, allowing accurately registered data to be interpreted according to the original context from which it was derived. Moreover, these strategies allow the presentation of group mean pressure data attained from prolonged pan colonic manometry studies, with substantially more clarity than has previously been achieved via histograms. Furthermore translation of data derived from HR colonic manometric recordings can be achieved. Most significantly, these methods permit observers to recognize the normal physiology of propagating pressure wave frequency and amplitude throughout the entire colon in health, and to readily distinguish key pathophysiological characteristics in constipation patients.

Our understanding of the pathophysiology that underpins constipation remains poorly understood. A lack of objective colonic pressure measures in adults continues to be a limitation to clinical advances, with only two small scale interventional studies currently based on evidence gained from colonic manometric investigation. In contrast, clinicians now routinely use oesophageal manometry to subtype swallowing disorders and predict treatment responses. There are several reasons for this discrepancy. The oesophagus is easily accessible and has relatively controlled motility. In addition, high-resolution oesophageal manometry has become the accepted norm with the generated spatiotemporal plots of pressure profiles allowing the uninitiated to quickly grasp the concepts of normal or abnormal pressure patterns.

Until recently HR manometry through-out the human colon was not possible. However, with the advent of fibre-optic pressure sensing technology, and the anatomically registered 3D visualization techniques presented here, we now have established the potential to acquire, analyze and interpret colonic motility data, identify manometric markers of dysmotility, and possibly define sub-types of constipation.

There are limitations to this technique. Applying an individuals data to a “stylized” colon negates the considerable variations in human anatomy. We can overcome this in
part by having fixed data points (i.e. the cecum, hepatic and splenic flexures and anus). This allow the remaining data between each of the fixed neighboring points to be linearly interpolated along the centre line of the virtual colon. In addition there exists several colonic forms in the visible human data set (IS THAT TRUE OR HAVE I JUST MADE THAT UP?) and an individuals data could be matched to a colon that more closely represents their own anatomy. Finally the interpolated grouped mean data do not allow for this display of the SEM or the SD at each colonic region. However, while potentially an issue, the main purpose of the 3D images is to portray the overall traits of the manometric data. The variance within the grouped mean data can be displayed in tables and in the applied statistics.
References

Figure 1. Spatiotemporal maps of propagating activity in a single healthy control (A) and a female patient with slow transit constipation [Dinning, 2010 #2267]. Within each map the ridges represent antegrade (green) and retrograde (red) propagating sequences (PS). The maps highlight the spatiotemporal distribution and amplitude of propagating sequences. Histograms can be used to display the amplitude (C) and wave frequency (D) data over the colonic regions for groups of patients and control subjects.
Figure 2. (A), (B), (C), and (D) show pressure amplitude (mmHg) and propagating pressure wave frequency (cumulative frequency) from data in Fig 1 (C) & (D). (A) and (C) show data from the control groups, (B) and (D) represent the patient groups. Note that in health the amplitude of propagating pressure waves increases at the splenic flexure and descending colon (A) and that this region also represents the area of greater pressure wave frequency (C). In contrast the amplitude of propagating pressure waves remains constantly low through the colon in patients with slow transit constipation (B) and they display a reduced frequency of pressure waves at the distal transverse colon and splenic flexure (D). A fluoroscopic image of the high-resolution catheter in a subsection of the colon is shown in (E) with the cumulative frequency of propagating pressure waves recorded in this single patient displayed in (F).