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

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Abstract

Colonic propagating sequences (PS) are important for the movement of colonic content and defecation, and aberrant PS patterning has been associated with slow-transit constipation. However, because these motor patterns are typically recorded over long periods (24 hrs.+), the visualization of PS spatiotemporal patterning is difficult. Here we develop a novel method for displaying pan-colonic motility patterns.

Methods—A 3D mesh representing the geometry of the human colon was created as follows: i) Human colon images from the Visible Human Dataset were digitized to create a 3D data cloud; ii) A surface mesh was fitted to the cloud using a least-squares minimization technique. Colonic manometry catheters were placed in the ascending colon of healthy controls and patients with slow transit constipation (STC), with the aid of a colonoscope. The colonic manometry data were interpolated and mapped to the model according to the following anatomical landmarks: caecum, hepatic flexure, splenic flexure, sigmoid-descending junction, and anus.

Key Results—These 3D images clearly and intuitively communicate characteristics of normal and abnormal colonic motility. Specifically we have shown the reduced amplitude of the antegrade propagating pressure waves (PPW) throughout the colon and reduced frequency of PPWs at the mid-colon in patients with STC.

Conclusion and inferences—A novel method for the 3D visualization of colonic propagating sequences is presented, providing an intuitive method for representing a large volume of physiological data. These techniques can be used to display frequency, amplitude or velocity data, and will help to convey regions of abnormally in patient populations.

Keywords

colon; constipation; three-dimensional visualization; manometry; fiber-optic

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Introduction

Constipation is a common and distressing condition that conveys a major socioeconomic and disease burden^{1, 2}. Disregulated colonic contractile activity is implicated in constipation^{3, 4} yet quantitative data unequivocally differentiating normal from abnormal colonic function is lacking⁵. This is due to several technical and analytical barriers that prevent the accurate manometric profiling of colonic luminal pressure patterns.

Previous colonic manometric studies have utilised catheters with ≤ 16 sensors spaced at ≥ 5 cm intervals^{6, 7}. While these studies have provided important insights into dysmotility associated with constipation, they lack the detail currently achieved by high-resolution (HR) manometry approaches in other gut regions, notably the oesophagus⁸. To overcome this problem, we recently developed a novel high-resolution fibre-optic manometry catheter capable of pan-colonic recordings at 1cm intervals⁹.

Whilst HR colonic manometry offers the potential to yield 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, generating 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 abnormalities⁴. Moreover, whilst we have previously developed a technique of spatiotemporal mapping colonic propagating pressure waves¹⁰, 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 three dimensional (3D) virtual modeling.

Methods

Patients and controls

Presented data were obtained from two 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. Methods and protocols for water perfused and fiber-optic manometric recordings have been described in detail elsewhere^{4, 9}.

Data Extraction

Propagating pressure waves (PPWs) were identified via semi-automated marking using custom software (St. George Clinical School, Sydney, Australia), written in Matlab (The MathWorks, MA) and Java (Sun Microsystems, CA). Definitions of propagating sequences (PSs) and PPWs have been previously defined¹¹; briefly, a PS was defined as an array of 3 or more propagating pressure waves recorded from adjacent recording sites in which the conduction velocity between wave onsets within that sequence lay between 0.2 and 12 cm/sec¹¹. Propagating sequences were further qualified by the terms antegrade or retrograde, depending upon the direction of propagation.

Anatomical Registration and Visualization—The 3D model framework employed in this study was translated from methods described by Fernandez et al¹². A 3D data cloud was created by digitizing the surface of the human colon using serial slices of the Visible

Human Dataset¹³. A 3D finite element surface was then fitted to the data cloud, using a least squares minimization technique¹². 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 = caecum, region 4 = hepatic flexure, region 8 = splenic flexure, region 12 = proximal sigmoid colon, region 16 = rectum)¹¹. Recording side holes were assigned to the colonic region within which they lay, with side hole 1 always in region 1⁴. For the HR studies, a plain abdominal x-ray was taken (Figure 1(G)), and all recording sensors were identified and assigned anatomical sites according to their observed 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^A, which allowed the manometry data to be easily converted to a file format that could be read into the visualization component of the CMISS software^B, called CMGUI visualization software. CMISS is a mathematical modelling and simulation environment for solving bioengineering problems developed at the University of Auckland. CMGUI was then applied to display the data in a visual format (i.e. spectrum range, orientation etc.) desired^C. 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 3D walls of the virtual colon. As an example, Figure 1(A) shows a theoretical set of pressure transducers (large spheres), colored with a pressure distribution, located on the virtual catheter. Figure 1(B) shows the data linearly interpolated along the virtual catheter. The interpolated data are then projected orthogonally onto the walls of the virtual colon to produce images such as Figure 1(C)-(F), (H).

To validate these methods, we present the cumulative frequency and amplitude of the antegrade PPWs per colonic region. These data have been recently been published in a less intuitive format^{4,9}. A white-blue spectrum was used to visualize the PPW cumulative frequency data over the 3D model, where white indicates no pressure waves and dark blue indicates the highest frequency of PPWs. The average amplitudes of PPWs per colonic regions are shown using a white-red spectrum.

Results are displayed together with previous methods (spatiotemporal maps and standard histograms) for comparison⁴.

Results

Standard spatiotemporal maps of a healthy control and a patient with slow transit constipation are presented in Figure 2(A),(B). These demonstrate the visualization of propagating sequence data for individual subjects, highlighting abnormal motility profiles⁴. However grouped mean data cannot be displayed by these methods, and are instead presented as histograms (Fig. 2(C),(D)). These histograms can be unintuitive with multi-sensor data and become prohibitively complex with HR data (72 sensors). Histograms could

^A<http://www.perl.org/>

^B<http://www.cmiss.org/>

^CTechnical details of this process are available from the authors

be simplified by binning data into anatomical regions (e.g. ascending, transverse, descending colon), however that would defeat the purpose of recording with multiple sensors.

Grouped mean data presented using the novel 3D modeling approach are shown in Figures 1(C)-(F). These images clearly and intuitively communicate characteristics previously described in slow transit constipation patients: the reduced amplitude of the antegrade PPWs (Fig. 1(D)) and the paucity of PPWs at the distal transverse and splenic flexure (Fig. 1(F))⁴.

Importantly, the novel techniques developed here are ideally suited to HR data sets from individual or grouped patients. Figure 1(G) shows the fiber-optic catheter positioned in a slow transit constipation patient. The cumulative frequency of the PPWs recorded at each sensor over a 24-hr period is shown interpolated on Figure 1(H). In this patient, PPWs are shown to occur in the transverse and sigmoid colon, but there is a marked reduction of activity throughout the entire descending colon.

Discussion

Novel approaches for the anatomical registration and 3D visualization of pan-colonic manometry data are presented. This 'pipeline' of methods effectively condenses a vast volume of complex manometric data into an efficient and intuitive display format, while allowing the data to be interpreted according to its original context. Furthermore, these strategies allow the presentation of group mean pressure data with substantially greater clarity than is possible with histograms⁴. These methods are shown to be ideally suited to new HR colonic manometric approaches⁹.

Most significantly, these methods permit all observers to easily distinguish the normal physiology of PPW frequency and amplitude from the pathophysiological characteristics in patients with dysmotility.

The pathophysiology of constipation remains poorly understood. An ongoing lack of objective colonic pressure measurements in adults continues to limit clinical advances, with only two small interventional studies being based on colonic manometry evidence^{3, 14}. In contrast, clinicians now routinely use oesophageal manometry to subtype swallowing disorders and plan treatment⁸. There are several reasons for this discrepancy. The oesophagus is easily accessible and has relatively controlled motility. In addition, HR oesophageal manometry is now widely practiced and spatiotemporal pressure profile plots have become standard tools, quickly allow clinicians to learn and apply the technique¹⁵.

Pan-colonic HR manometry is now possible, following the advent of fibre-optic pressure sensing technology⁹, and together with these new anatomical registration and visualization techniques, we now have established improved potential to acquire, analyze and interpret colonic motility data, to identify manometric markers of dysmotility, and potentially to define new sub-types and mechanisms of constipation.

Important limitations to these methods should be noted. Foremost, applying an individual's data to a generic colon negates the considerable variations in anatomy. This is partly overcome by mapping the data to fixed anatomical reference points. However, in future, it would be more desirable to develop a library of generic templates, from which an appropriate geometric match can be selected, as is standard practice in functional brain imaging¹⁶. The geometries generated routinely using CT colonography, such as those presented in Hanson et. al.¹⁷ would provide an excellent source of patient specific or library models. Finally, the interpolated grouped mean data do not allow for this display of the SEM or the SD at each colonic region. However, the main purpose of methods is to accurately

portray manometric data traits, and variance can easily be presented in accompanying tables or text.

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Figure 1.

(A),(B) displays the interpolation method used to map the discrete pressure transducer data to the 3D virtual colon. (C), (D), (E), and (F) show pressure amplitude (mmHg) and PPW frequency (cumulative frequency) from data in Fig 2(C) & (D). (C) and (E) show data from the control groups, (D) and (F) represent the patient groups. The color spectrum denotes low activity/pressure with white, and high/activity pressure with dark blue/red respectively. Note that in health, the amplitude of PPWs increase at the splenic flexure and descending colon (C), and that this region also represents the area of greater wave frequency (E). In contrast, the amplitude of PPWs remains constantly low throughout the colon in patients with slow transit constipation (D) and a reduced frequency of PPWs occurs at the distal transverse colon and splenic flexure (F). A fluoroscopic image of the HR catheter in a subsection of the colon is shown in (G) with the cumulative frequency of PPWs waves recorded in this individual displayed in (H). A paucity of activity is evident in the splenic flexure and descending colon.

Figure 2.

(A),(B) show spatiotemporal maps of propagating activity in a single healthy control (A) and a slow transit constipation patient (B) ⁴. The ridges represent antegrade (green) and retrograde (red) propagating sequences (PS). The maps demonstrate the spatiotemporal distribution and amplitude of PSs. Histograms are used to display the amplitude (C) and wave frequency (D) data over the colonic regions for groups of subjects.