doi: 10.1109/JSEN.2011.2123883

Measurement of muscular activity associated with peristalsis in the human gut using fibre Bragg grating arrays

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ABSTRACT

Diagnostic catheters based on fibre Bragg gratings (FBG's) are proving to be highly effective for measurement of the muscular activity associated with peristalsis in the human gut. The primary muscular contractions that generate peristalsis are circumferential in nature; however, it has long been known that there is also a component of longitudinal contractility present, acting in harmony with the circumferential component to improve the overall efficiency of material movement. We report on the development of, and latest results from, catheter based sensors capable of detecting both forms of muscular activity. While detection of the circumferential contractions has been possible using solid state, hydraulic, and pneumatic sensor arrays in the oesophagus and anorectum, FBG based devices allow access into the complex and convoluted regions of the gut below the stomach. We report early results from FBG catheters used during trials of novel therapies in patients with both slow transit constipation and faecal incontinence. In addition, there have been relatively few reports on the measurement or inference of longitudinal contractions in humans. This is due to the lack of a viable recording technique suitable for real-time in-vivo measurement of this type of activity over extended lengths of the gut. We report preliminary data on the detection of longitudinal motion in lengths of excised mammalian colon using an FBG technique that should be viable for similar detection in humans. The longitudinal sensors have been combined with pressure sensing elements to form a composite catheter that allows the relative phase between the two components to be detected. The output of both types of catheter has been validated using digital video mapping in an ex-vivo animal preparation using lengths of rabbit ileum.

Fiber Bragg gratings; Optical fibre sensing; Gastroenterology; Medical optics instrumentation; Biophotonics

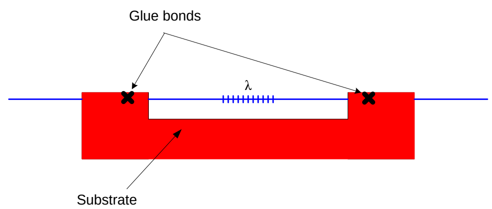
1. INTRODUCTION

The propulsion of intraluminal content throughout the gastrointestinal (GI) tract relies on the coordinated movements of the longitudinal and circumferential muscle layers in the gut wall, commonly known as peristalsis[1,2]. The relative movements of the two muscle layers in the gut wall have been the subject of much controversy over the past 100 years, largely due to the difficultly in measuring the contractility of these muscle fibres.

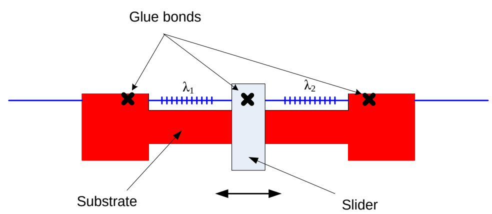
Fibre optic sensing is proving to be an effective means of gaining diagnostically significant recordings from the human body and in the recent past we have successfully recorded distributed variations in circumferential contractions in the human oesophagus and colon[3, 4]. In this work we present recent results from extended pan-colonic catheters and preliminary results from a composite catheter that simultaneously measures the longitudinal and circumferential activity at multiple points along a section of excised of rabbit ileum. The pan-colonic catheters are showing the amazing complexity of activity present in the human colon and have also provided a means for quantitative analyses of interventional techniques such as sacral nerve stimulation [ref] that obviates the need to reply on highly subjective patient 'Quality of Life' diaries for viable assessment of efficacy.

2. CATHETER AND DATA ACQUISTION

The catheters are formed from one or more fbg arrays supplied by FBGS. Importantly, these draw tower grating (DTG) arrays maintain the mechanical strength necessary to form viable mechanically stable catheters. The pan-colonic catheters consist of 3 fibre arrays with a total of 90 sensing elements spanning a total sensing length of 890mm (10mm spacing between sensor regions). The composite catheter has 5 pressure sensors and 5 longitudinal sensors spaced alternately on a 15 mm pitch to provide a distributed image of both circumferential and longitudinal action over a total length of 150 mm. The pressure sensors consist of a single FBG element fixed at either end of a rigid substrate and surrounded by a pressure sensitive diaphragm so that contractions of the circumferential muscles of the gut distort the fibre sideways, hence causing a change in the reflected wavelength. The longitudinal sensors are constructed from two axially separated FBG elements with an annular slider attached to the fibre between them and underneath the outer sleeve of the catheter. Since the slider is in contact with the outer sleeve, and the outer sleeve is in frictional contact with the wall of the gut, any relative motion of the wall past the catheter is picked up as a change in the reflected wavelengths of the two FBG's. Both the pressure and longitudinal sensing elements are shown schematically in Fig. 1. The data acquisition systems for the pan-colonic and composite catheters were based on commercially available solid state spectrographs from FOS&S (###) and IPhT respectively (BlueBox).



(a)



(b)

Fig. 1. Schematics of the fibre grating circumferential sensor (a) and longitudinal sensor (b). In both instances the sensor elements are covered by a protective biocompatible sleeve which has been omitted for clarity

3. IN-VITRO ANIMAL MODEL

To test the catheters in a controlled environment, adult male rabbits were euthanized in a manner approved by the Animal Welfare Committee of Flinders University. Segments of gut were removed and placed into an organ bath containing warm oxygenated Krebs solution bubbled with carbogen gas (95% O2/ 5% CO2). The catheter was introduced into the gut and dot markers (2mm X 2mm) were applied to the external surface above the locations of the sensors. A digital video camera was used to record any motion of the gut generated by the circumferential and longitudinal muscular activity. Figure 2 shows a schematic of the experimental set-up used.

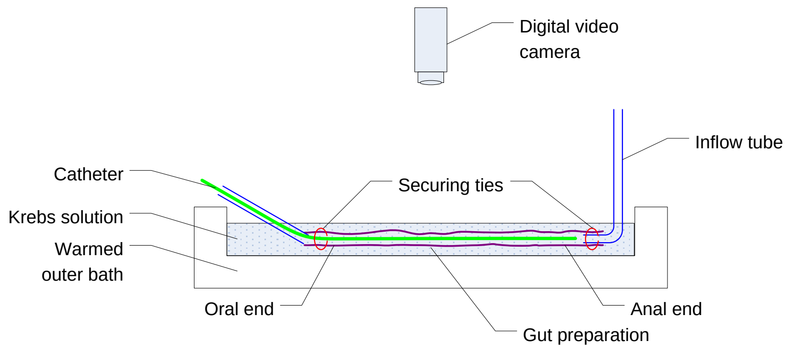


Fig. 2: Experimental set-up used to measure and image the muscular activity in the sections of rabbit ileum.

Initially, each preparation exhibited spontaneous longitudinal activity which was recorded for several minutes. No significant circumferential contractions were observed during this period. A small volume of Krebs solution was then introduced into one end of the ileum via the inflow tube shown in Figure 2 to provide a sufficient distension stimulus to evoke circumferential activity. The combined effects of circumferential and longitudinal activity propelled the infused liquid along the gut and back up the inflow tube. When the gut relaxed the liquid flowed back into the gut under gravity and the cycle repeated.

4. RESULTS

4.1 Circumferential sensing

The data recorded from the catheters was validated against the digitized output from the video camera. To visualize the camera output, a diameter mapping technique was used [ref] in which the local diameters of the gut were automatically recorded for each frame of the video and then converted into a gray scale image with time along the x-axis and location along the y-axis. The resulting map provides an image of the local diameters along the section of gut under evaluation with white indicating small diameters and black the larger diameters. This enables the variations in diameter over time to be viewed in a single image. For the pressure sensing catheter, a section of gut with all connective tissue and fatty deposits removed was used. This ensured that variations in diameter were due only to circular muscular contractions. # sections of gut were evaluated and the results are sumarised in Table #.

4.2 Longitudinal sensing

During the initial longitudinal muscle activity the output signals from the longitudinal sensors were well correlated with the longitudinal motion observed using the video camera. The image in Figure 3 shows a diameter map[5] made of the section of gut surrounding the first two pressure and longitudinal sensors with the output from both longitudinal (red traces) and circumferential (green traces) sensors overlaid on the image. Since the section of gut used for this measurement was not trimmed prior to use, the outer surface of the gut was highly irregular, this provided an easy way of visualizing the longitudinal motion as regions of varying diameter moved across the video image. The catheter signals showed that there was no significant circumferential activity present during the recording and also that the longitudinal signals from the catheter were highly correlated with the longitudinal activity recorded by the video camera.

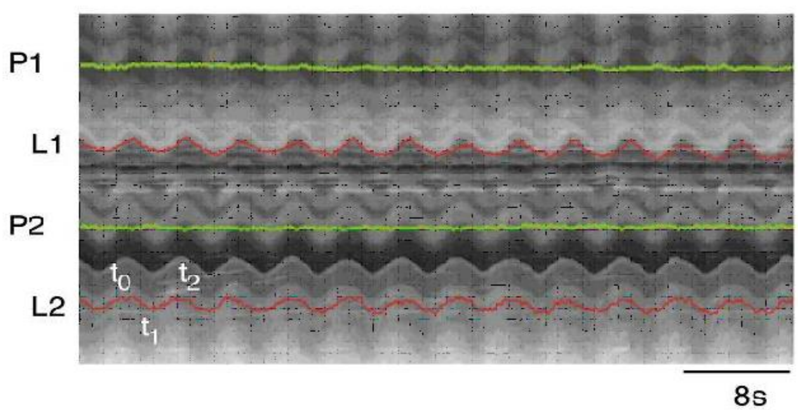


Fig 3. Example of longitudinal movement only in the rabbit ileum shown on a diameter map created from the digital video footage. The ripples in the map indicate the change in diameter in time. The green and red lines represent the location of the circumferential and longitudinal sensors (see text for more detail).

4.3 Combined pressure and longitudinal sensing

The combined action of the composite catheter was then tested in the same set up as described in Section 4.2 above. Distention of the lumen by the introduced Krebs solution stimulated strong, circumferential contractions in addition to the longitudinal contractions. Figure 4 shows the recording from the longitudinal (red) and pressure (green) sensors during two cycles of activity. In this instance the pressure sensors picked up the propagating circumferential contraction (pressure wave) that moves along the length of gut, including a pause in propagation during the second cycle that was also clearly visible on the video footage. The longitudinal sensors also pick up the coordinated longitudinal muscle activity associated with the pressure wave. While it is difficult to fully quantify the amplitude of the longitudinal activity it has been conjectured that it is the relative phase between circumferential and longitudinal contractions that may prove diagnostic of some gastrointestinal motility disorders so it is this aspect of the signal that will form the key component of on-going trials of this technology in humans.

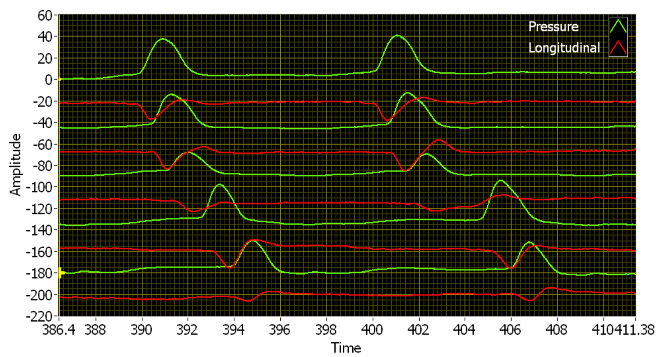


Fig 4. Example of simultaneous recording of longitudinal and circumferential movement in the rabbit ileum (circumferential = green; longitudinal = red).

4.4 In-vivo pan-colonic studies

The pan-colonic catheters have now been used in a series of in-vivo studies of patients undergoing trials of a new form of therapy based on electrical stimulation of nerves in the sacrum [ref]. The studies involve placement of the catheter into regions of the colon ranging from the caecum to anorectum and recording muscular activity during a sequence of sham and real nerve stimulation. Patients with both faecal incontinence (FI) and slow transit constipation (STC) have been tested in this manner. Figure # shows a recording from # minutes of high colonic activity in a FI patient, and Figure # shows the response to sacral nerve stimulation in a STC patient. The activity shown in Figure # (FI data) demonstrates the complexity and bipolar nature of the muscular contractions, while Figure # (STC/SNS data) clearly shows an increase in activity as a result of the stimulation. Figure # (STC after switch on) shows an expanded region of data after stimulation, again showing the complexity of muscular activity running in both directions along the gut. Full analyses of these data are currently underway and will be presented in medical journals once an acceptable patient cohort has been established.

5. CONCLUSIONS

Catheters capable of recording both circumferential and longitudinal muscular activity have been successfully trialed in sections of rabbit gut. The output from the pressure and longitudinal sensors qualitatively mimic the circumferential and longitudinal motion of the gut wall as viewed by a digital video camera and the combination of pressure and longitudinal sensors can record the phasing between circumferential and longitudinal contractions. Catheters based on the pressure sensing mechanism have been successfully used in-vivo in patients undergoing sacral nerve stimulation tirals for both FI and STC and have demonstrated both the complexity of muscular contractions present in both patient sub-groups and also have provided a means for qualitative analysis of the response to nerve stimulation therapy which should avoid the need to rely on subjective descriptions of response given in follow ups with patients.

ACKNOWLEDGEMENTS

Dr’s Dinning and Szczesniak are supported by NHMRC grant #630502; and Dr Spencer is supported by NHMRC grant #535034.

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