Measurement of Muscular Activity Associated With Peristalsis in the Human Gut Using Fiber Bragg Grating Arrays

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***Abstract*—Diagnostic catheters based on fiber 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. While detection of the circumferential contractions has been possible using solid state, hydraulic, and pneumatic sensor arrays in the oesophagus and anorectum, there have been relatively few reports on the measurement or inference of longitudinal contractions in humans. This is partly 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 on the development of, and latest results from, catheter based sensors capable of detecting both forms of muscular activity. Results from validation trials of both circumferential and longitudinal FBG catheters during simultaneous recording and video analysis in lengths of excised mammalian colon are given. Preliminary data from human clinical trials in patients with functional gastrointestinal disorders of the colon are also presented demonstrating the ability of the fiber optic catheter technology to provide high resolution data from the complex and convoluted regions of the human gut below the stomach.**

***Index Terms*—Biophotonics, fiber Bragg gratings, gastroenterology, medical optics instrumentation, optical fiber sensing.**

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I. 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 fibers.

Fiber optic sensing is proving to be an ideal technology for distributed sensing in difficult to access environments [3], [4] and these same attributes are being increasingly applied for in-vivo sensing. Specifically, fiber Bragg grating sensors are providing 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 [5], [6]. In this work we present recent results from both a circumferential sensing catheter and a composite catheter that measures the longitudinal and circumferential activity simultaneously at multiple points along the length of the catheter. The performance of the two types of sensors have been validated using simultaneous video footage taken during an in-vitro trial in a section of excised rabbit ileum. The viability of this technology for prolonged recording in the human body has also been demonstrated in a series of clinical trials on patients suffering from Functional Gastrointestinal Diseases (FGIDs) of the colon.

II. Catheter and Data Acquistion

The catheters are formed from one or more fiber Bragg grating (FBG) arrays supplied by FBGS technologies (http://www.fbgs-technologies.com). 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 fiber arrays with a total of 90 sensing elements spanning a total sensing length of 890 mm (10 mm 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

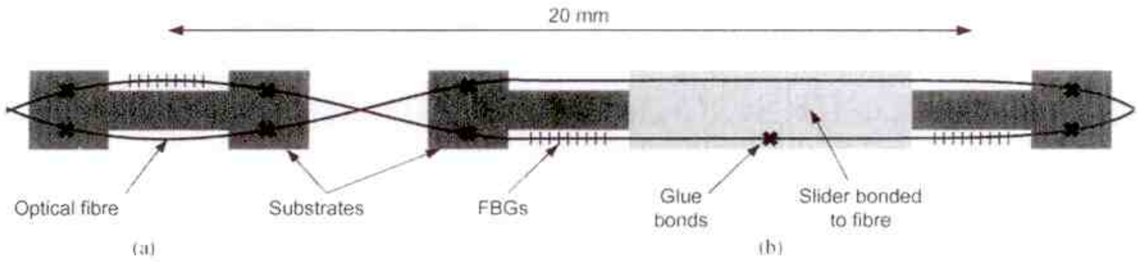

Fig. 1. Schematic of the fiber grating circumferential sensor (a) and longitudinal sensor (b). The sensor elements are covered by a protective biocompatible sleeve which has been omitted for clarity.

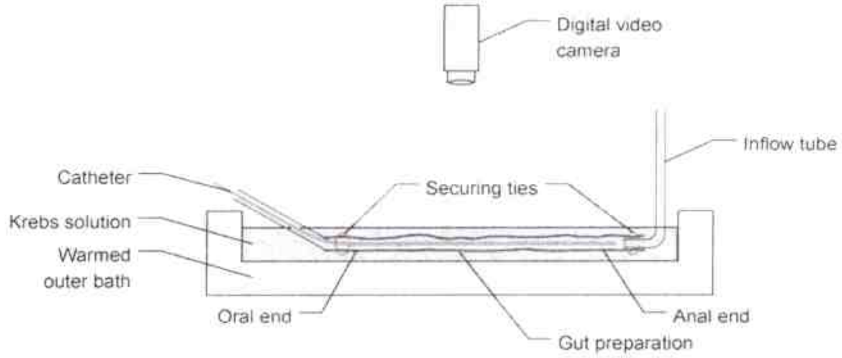

Fig. 2. Experimental setup used to measure and image the muscular activity in the sections of rabbit ileum.

surrounded by a pressure sensitive diaphragm so that contractions of the circumferential muscles of the gut distort the fiber 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 region of fiber 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. It is important to note however that, due to the sensitivity of the FBGs, the absolute motion of the sliders is only of the order of 50 um and so displacement of the outer sleeve in one location is not appreciably transferred to other regions of the catheter. Both the pressure and longitudinal sensing elements are shown schematically in Fig. 1; more details of the catheter calibration can be found elsewhere [7]. The data acquisition systems for the pan-colonic and composite catheters were based on solid state spectrographs from FOS&S (custom made unit) and IPhT (the "BlueBox") respectively.

III. 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 (2 mm $\times$ 2 mm) 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. Fig. 2 shows a schematic of the experimental setup used.

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 Fig. 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.

IV. Results

A. Circumferential Sensing

The output recorded from the circumferential catheter was validated against the digitized output from the video camera. To visualize the camera output, a diameter mapping technique was used [8] 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 this study, all connective tissue and fatty deposits were removed from the sections of gut so that the outer diameter of the gut was smooth and of nominally constant diameter. This ensured that any variations in diameter picked up by the video imaging were due to circular muscular contractions only. A total of 90 minutes of data from both the catheter and

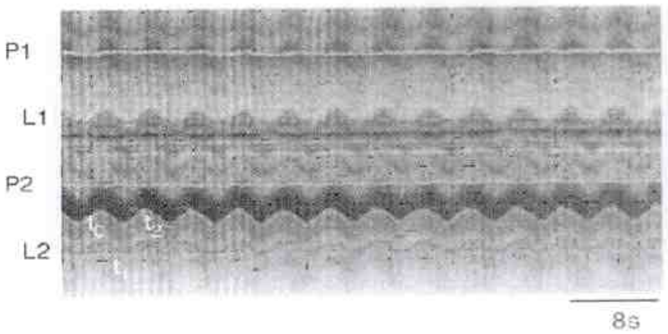

Fig. 3. Example of longitudinal movement only in the rabbit ileum shown on a diameter map created from the digital video footage. The ripples in the map indicate the change in diameter in time. The green and red lines represent the location of the circumferential and longitudinal sensors (see text for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

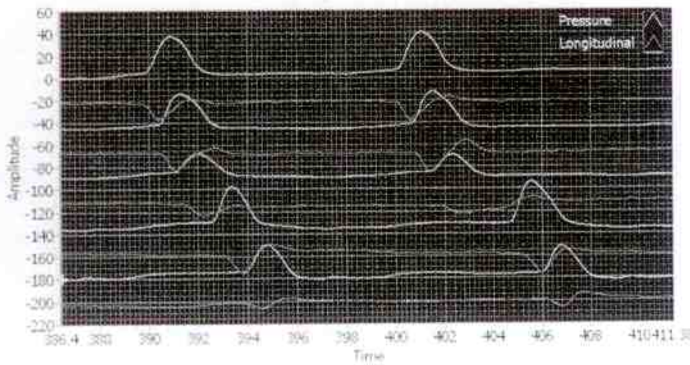

Fig. 4. Example of simultaneous recording of longitudinal and circumferential movement in the rabbit ileum (circumferential = green; longitudinal = red).

video were analysed with 89% of the observed propagating contractions seen on the video being identified as propagating by the catheter [9]. Note that the definition of 'propagating' used for the catheter data requires coordinated events to be picked up by a minimum of 3 consecutive sensors and so short range propagating events were sometimes identified by the video image but not by the catheter. These short range events accounted for a further 8% of the contractions seen on the video giving a total of 97% agreement between the two means of analysis.

B. Longitudinal Sensing

For the composite catheter, the output signals from the longitudinal sensors were well correlated with the longitudinal motion observed using the video camera. The image in Fig. 3 shows a diameter map 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, and 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.

C. Combined Pressure and Longitudinal Sensing

The combined action of the composite catheter was then tested in the same set up as described in Section IV-B above. Distension of the lumen by the introduced Krebs solution stimulated strong, circumferential contractions in addition to the longitudinal contractions. Fig. 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.

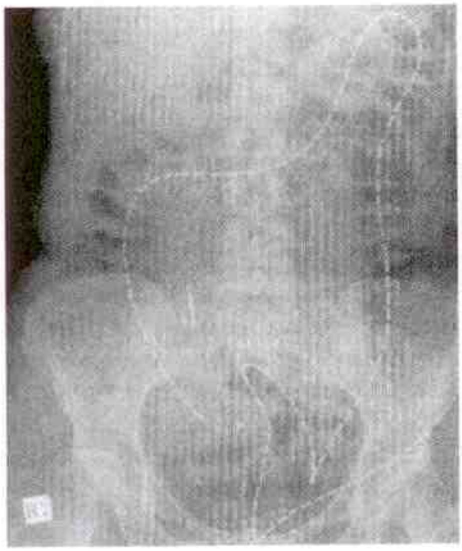

Fig. 5. X-ray image of patient with chronic FGID undergoing a motility study with a fiber optic manometry catheter clipped to the mucosa close to the caecum.

D. In-Vivo Pan-Colonic Studies

The pan-colonic circumferential sensing catheters have now been used in a series of in-vivo studies of patients with chronic functional gastrointestinal disorders (FGID's) [10]. The studies involve colonoscopic placement of the catheter into regions of the colon ranging from the caecum to the anorectum and recording muscular activity during a sequence of controlled diagnostic interventions. Fig. 5 shows an X-ray image of the catheter advanced to the caecum of a patient with chronic slow transit constipation (STC). Fig. 6 shows a recording from 6 minutes of colonic activity in a different patient, demonstrating the complexity and bidirectional nature of the muscular contractions present. The outcomes of the trials will be reported in the medical literature once acceptable patient numbers have been evaluated.

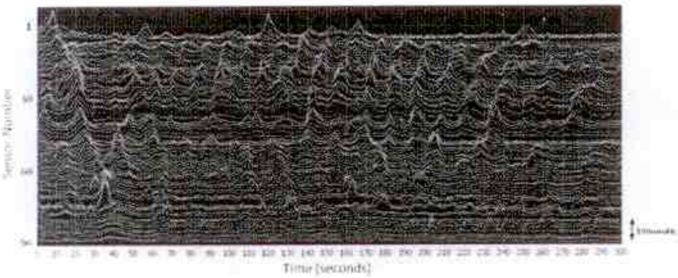

Fig. 6. Example of the complexity of data recorded using the pan-colonic fiber optic catheters showing the bidirectional nature of the contractions present.

V. Conclusions

Catheters capable of recording both circumferential and longitudinal muscular activity have been successfully trialled in excised 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. While the pressure sensors accurately record intraluminal pressures, it is difficult to attribute quantitative values to the longitudinal sensor output (due to variations in frictional contact between the lumen and catheter). However, the combination of pressure and longitudinal sensors can record the phasing between circumferential and longitudinal contractions, which is believed to be of diagnostic significance in some FGIDs. Catheters based on the pressure sensing mechanism have been successfully used in-vivo in patients with chronic FGID demonstrating the viability of this technology for prolonged use in the human body.

References

[1] N. J. Spencer and T. K. Smith, "Simultaneous intracellular recordings from longitudinal and circular muscle during the peristaltic reflex in guinea-pig distal colon," *J. Physiol.*, vol. 533, pp. 787–779, 2001.

[2] N. J. Spencer, M. Walsh, and T. K. Smith, "Does the guinea-pig ileum obey the "law of the intestine"?," *J. Physiol.*, vol. 517, pp. 889–898, 1999.

[3] Y. J. Rao, "Recent progress in applications of in-fiber Bragg grating sensors," *Opt. Lasers Eng.*, vol. 31, no. 4, pp. 297–324, Apr. 1999.

[4] . J. M. Lopez-Giguera, Ed., *Handbook of Optical Fiber Sensing Technology*. Chichester, U.K.: Wiley.

[5] J. W. Arkwright, I. D. Underhill, S. A. Maunder, N. G. Blenman, M. M. Szczesniak, L. Wiklendt, D. Z. Lubowski, I. J. Cook, and P. G. Dinning, "Design of a high-sensor count fiber optic manometry catheter for in-vivo colonic diagnostics," *Opt. Exp.*, vol. 17, pp. 22423–22431, 2009.

[6] J. W. Arkwright, N. G. Blenman, I. D. Underhill, S. A. Maunder, M. M. Szczesniak, P. G. Dinning, and I. J. Cook, "In-vivo demonstration of a high resolution optical fiber manometry catheter for diagnosis of gastrointestinal motility disorders," *Opt. Exp.*, vol. 17, pp. 4500–4508, 2009.

[7] J. W. Arkwright, N. G. Blenman, I. D. Underhill, S. A. Maunder, N. J. Spencer, M. Costa, S. J. Brookes, M. M. Szczesniak, and P. G. Dinning, "A fiber optic catheter for simultaneous measurement of longitudinal and circumferential muscular activity in the gastrointestinal tract," *J. Biophoton.*, Jun. 23, 2010, to be published.

[8] G. W. Hennig, M. Costa, B. N. Chen, and S. J. Brookes, "Quantitative analysis of peristalsis in the guinea-pig small intestine using spatio-temporal maps," *J. Physiol.*, vol. 517, pp. 575–590, 1999.

[9] P. G. Dinning, M. Costa, J. W. Arkwright, L. Wiklendt, G. Hennig, S. J. Brookes, and N. J. Spencer, "Relating gut movement and intraluminal manometry in the isolated rabbit small intestine," *Gastroenterol. Hep.*, vol. 25, no. 3, p. A104, 2010.

[10] J. W. Arkwright, M. M. Szczesniak, L. Wiklendt, D. Z. Lubowski, and P. G. Dinning, "High resolution fiber optic colonic manometry in patients with slow transit constipation indicates the potential of signal aliasing and misinterpretation of propagating events," in *Proc. ANS/AuPS 2010*, Sydney, Australia, 2010, Paper ORAL-06-04.

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Neil G. Blenman, photograph and biography not available at the time of publication.

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