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The effect of luminal content and rate of occlusion on the interpretation of colonic manometry

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Abstract:

Background

Manometry is commonly used for diagnosis of esophageal and anorectal motility disorders. In the colon, manometry is a useful tool, but clinical application remains uncertain. This uncertainty is partly based upon the belief that manometry cannot reliably detect non-occluding colonic contractions and, therefore, cannot identify reliable markers of dysmotility. This study tests the ability of manometry to record pressure signals in response to non-lumen-occluding changes in diameter, at different rates of wall movement and with content of different viscosities.

Methods

A numerical model was built to investigate pressure changes caused by localized, non-lumen-occluding reductions in diameter, similar to those caused by contraction of the gut wall. A mechanical model, consisting of a sealed pressure vessel which could produce localized reductions in luminal diameter, was used to validate the model using luminal segments formed from; i) natural latex; and ii) sections of rabbit proximal colon. Fluids with viscosities ranging from 1mPa.s to 6800mPa.s and luminal contraction rates over the range 5 – 20 mmHg/s were studied.

Key Results

Manometry recorded non-occluding reductions in diameter, provided that they occurred with sufficiently viscous content. The measured signal was linearly dependent on the rate of reduction in luminal diameter and also increased with increasing viscosity of content (R^2= 0.62 and 0.96 for 880 and 1760 mPa.s respectively).

Conclusions & Inferences

Manometry reliably registers non-occluding contractions in the presence of viscous content, and is therefore a viable tool for measuring colonic motility. Interpretation of colonic manometric data, and definitions based on manometric results, must consider the viscosity of luminal content.

Keywords: Manometry, motility, gastroenterology, functional gastrointestinal disorders

Introduction

The primary tool for investigating motility disorders in the oesophagus and anorectum is manometry; it has provided valuable insight into normal and abnormal motility patterns in these regions 1, 2. However, manometry in the adult colon is largely considered a research-only tool 3, based in part on the belief that colonic manometry can only detect a small subset of contractile activity.

For example, it has been suggested that manometry will only record lumen occluding muscular contractions; that is, contractions in which the wall physically squeezes the catheter 4. As the diameter of the colon may exceed 50 mm and manometry catheters are relatively thin (3-5mm), it is often assumed that colonic manometry may miss the majority of wall movements 5. This assumption, which may be important for guiding manometric interpretations, has been supported by combined manometry and barostat studies that inferred up to 70% of contractile events are not recorded on manometry, when the colonic diameter exceeds 5.6cm 5. However, manometric recordings in children with dilated colons have reported normal motility patterns 6. In addition, non-lumen occluding contractions have been recorded manometrically in the proximal colon 7, stomach 8, and esophagus 9 of adults.

Manometry records intraluminal pressure and/or force generated by muscular contractions. A critical consideration determining manometric signals is how the force generated by the muscular contraction is transmitted to the manometric sensor. If the lumen is either closed, or in contact with a solid body such as the manometry catheter, then muscular contraction will be essentially isometric. In these cases, the contractile force acts directly on the sensor and a large signal results. Conversely, if there is deformable content within the lumen then wall movement will cause the content to redistribute itself along the lumen, and the signal may be transient and/or of small peak amplitude. In the latter case, contractions can propel fluid or gaseous content rapidly, while generating relatively low luminal pressures 10.

The aim of this study was to provide an improved numerical and physical foundation for interpreting manometric studies, by investigating the relationships between (i) the rate of reduction in luminal diameter and (ii) the viscosity of luminal content on the measured intraluminal pressure. We hypothesized that the signal recorded by a manometric catheter is positively correlated with both the rate of movement of the gut wall and by the viscosity of luminal content. Accordingly, luminal diameter *per se*

is not a reliable predictor of the manometric signals. This hypothesis was investigated by both *in-silico* numerical and *in-vitro* experimental methods.

Materials and Methods

Numerical model

A numerical model of a short section of lumen with a localized region that could undergo physical deformation surrounded by non-local reductions in diameter was built using COMSOL (COMSOL Multiphysics, COMSOL Inc., Palo Alto, CA, USA), a commercially available multiphysics modelling and simulation software package. Figure 1 shows the geometry of the COMSOL model that represents the central section of the experimental setup (explained in greater detail below), as explained in detail in the next section. The model was used to investigate how pressure measured on the axis of the lumen is affected by variations in viscosity of luminal content, and also rate of collapse of a localised section of lumen.

For more efficient computation, a number of simplifying assumptions were made:

1. The numerical model did not attempt to take into account the visco-elastic nature of the natural tissue. Therefore, visco-elastic creep was not simulated as pressure was applied to the external pressure vessel.
2. The complicated geometry of the experimental setup was simplified to a single tube with two diameters, representing the main structure of the lumen, cannulae, and the flexible tubes to the reservoirs (Figure 1 & 2)
3. In order to apply 2D axial symmetry, the flexible tubes linking the pressure vessel to the reservoirs were drawn parallel to the lumen.
4. A uniform cylindrical shape was assumed for the starting geometry of the lumen.

In addition, during execution of the model, the deformation of the luminal wall was solved independently of intraluminal content. Therefore, forces due to the fluid acting outwards onto the wall were not considered, which would increase with increasing fluid density or decreasing tube size. Open boundary conditions were specified at both ends of the model. This ensured zero internal pressure at resting conditions, as obtained during the experimental recordings.

To investigate the effect of contraction rate, Gaussian-like pressure profiles up to the maximum applied pressure of 50 mmHg were applied to the external surface of the central luminal segment, followed by a ramp down to 0 mmHg, over intervals of 5 s, 10 s and 20 s.

The effect of luminal fluid viscosity was investigated by solving the fluid mechanics with two representative dynamic viscosities (780 mPa.s and 5000 mPa.s) for each pressure profile.

Both *in-vitro* and *in-silico* models were built based on an active return of the lumen to its starting shape. In real colonic contractions, the mere cessation of active contraction would not cause the lumen to expand outwards of its own accord. The musculature would instead relax back to a flaccid state, eventually expanding back to the original dimensions as digesta flows in from neighbouring regions. Nevertheless, the model was designed to allow a sufficiently realistic representation of the physical conditions of luminal contractions underlying manometric interpretations

In-Vitro Model

The in-vitro experimental work carried out to validate the *in-silico* model used a pressure vessel capable of imposing a localised reduction in diameter in a luminal section of common internal diameter. The pressure vessel was based on an apparatus design by Dent et al 11 for the testing of water perfused sleeve catheters and is shown schematically in Figure 2. All experiments utilising animal tissue were approved by the Animal Welfare Committee of Flinders University.

The pressure vessel contained two thin-walled cannulae located on a common central axis, each having an internal diameter of 11.8 mm, separated by a 20 mm gap. The luminal segment under test was tied to the cannulae to produce a water-tight seal, under sufficient longitudinal tension to ensure that the lumen was open and the luminal wall approximately cylindrical in shape.

The cannulae were connected to T-pieces to allow a manometry catheter with sensors at 10mm intervals to be fed through the lumen and pressure-sealed at both ends. The upright arms of the T-pieces were connected to large-volume reservoirs that allowed the required luminal fillers to be gravity-fed into the internal region of the cannulae and lumen under test. The sealed outer region of the pressure vessel itself

was filled with water and connected to a syringe so that the lumen could be deformed hydraulically in a controllable fashion (Figure 2). This allowed the lumen to be collapsed inwards over the 20 mm gap at different rates, towards its axis to simulate a localised muscular contraction. Applying the pressure hydraulically prevented any pressure induced changes in temperature occurring at the outer surface of the lumen that could have adversely affected the recordings.

Two types of lumen were used. Firstly, we studied sections of latex rubber. Secondly; sections of natural proximal colonic tissue obtained from four female New Zealand albino rabbits each weighing approximately 2 Kg. Following euthanasia by intravenous injection of sodium pentobarbitone (0.5 ml/kg), a ventral midline incision was performed and segments of proximal colon were removed, flushed of luminal content and placed in distilled water at room temperature to suppress spontaneous muscular activity. The proximal rabbit colon was specifically selected because it contains 3 bands of tenia and has a diameter (15 mm) of sufficient width to accommodate a manometery catheter (3 mm). Thus the section of gut was not distended by the catheter, nor was it 'squeezing' the catheter in its non-occluded state.

The rubber material was more controllable than the colonic segment and formed more uniform cylindrical segments that were better matched to the numerical model described above. The natural tissue was used to test whether results with latex were comparable to those of the more viscoelastic gut tissue 12.

Luminal segments of either latex rubber or rabbit colon approximately 50 mm long were introduced over the ends of the cannulae and tied in place as described above (n=5 from 4 rabbits for the colonic lumen). In both cases, the segments collapsed, as expected, in response to increases in pressure applied to the outer pressure vessel. However, the slow visco-elastic creep of the sections of rabbit colon allowed the lumen to accommodate to the changes of pressure 12, resulting in a non-linear relationship between the depression of the syringe plunger (see below) and the applied pressure. Because of this, only the initial rate of rise of the catheter response, corresponding to the approximately linear period of pressurisation, was used for analyses when studying specimens of rabbit colon.

Manometry catheter

A high resolution fibre optic catheter fabricated at CSIRO (CSIRO Materials Science and Engineering, Lindfield, NSW 2070, Australia) was used for the experimental studies. The device was 3 mm in diameter and contained 32 pressure sensing elements spaced at 10 mm intervals along the axis. The outer surface of the catheter was formed from a continuous silicone sleeve and had no inclusions or variations in outer diameter associated with the sensing regions. The design, operation and validation of the catheter have been described in detail previously 13, 14.

The catheter was fed through the central lumen within the pressure vessel and held at proximal and distal regions using the pressure seals indicated in Figure 2. The catheter was held under a slight axial tension so that it was constrained to lie along the common axis of the cannulae and lumen.

Viscous fillers

The viscous filler to be tested was poured into one reservoir and allowed to flow into and through the internal region of the lumen. Four luminal fillers of differing viscosity, simulating colonic contents, ranging from ~200 to ~7000 mPa.s were prepared. Water was used as a control (viscosity = 1mPa.s) and thicker fillers were made by dissolving Methylcellulose (Product # 274429, Sigma Aldrich, Australia) into warmed water and left overnight to gel. The viscosity of each prepared mixture was verified with a hand-held viscometer (Brookfield Synchro-Lectric Viscometer, Model RVF) immediately prior to use. For the more viscous fillers, the liquid was drawn through the internal region using a syringe pressed into the lower aperture of the second reservoir. Air bubbles that lodged in the region of the luminal segment were displaced prior to the start of measurements.

Experimental protocol

Degree of Occlusion

First, we determined how much the luminal diameter needed to be reduced for the wall to directly contact the catheter was determined with no luminal filler present. The luminal segment was collapsed by depressing the syringe plunger in a step-wise manner and the resulting change in pressures registered by the catheter were recorded. The graph in Figure 3 shows a typical result from one such test. The

sensor located mid-way between the ends of the cannulae and directly at the centre of the lumen shows increasing pressure from the moment the luminal wall first makes contact with the catheter. The responses from nearest the neighbouring sensors along the catheter remained unchanged, indicating that the catheter was correctly located within the lumen. Thereafter, the range of movement of the syringe plunger was then limited to ~80% of the point of occlusion to prevent physical contact between the lumen and the catheter.

Dynamic Response

Once the point of occlusion had been determined, one of the reservoirs was filled with liquid of the desired viscosity. The syringe was then depressed, forcing the walls of the luminal segment (latex or rabbit colon) to constrict in a series of phasic pressure events, each with a different rate. For one section of rabbit colon the events pressure changes were repeated multiple times using two different viscosities (880 and 1760mPa.s), in order to generate statistically significant data.

Results

In-silico results

The calculated changes in pressure on the axis of the lumen during a sequence of non-occluding events, using luminal fluid with viscosities of 780 and 5000mPa.s, in response to localised reductions in diameter are displayed in Figure 4. As the luminal diameter reduced, the fluid pressure increased due to viscous forces and the restricted diameter at the ends of the lumen. However, as fluid continued to flow out of the contracted region, pressure rapidly decreased even as the wall continued to deform inwards. As the lumen gradually returned to its starting position, the intraluminal pressure dropped below zero. It is interesting to note that the intraluminal pressure starts to increase rapidly even at the very early stages of the reduction in diameter. This trend was also present in the *in-vitro* investigations as described below (Figure 5).

The intraluminal pressure increased faster when using intraluminal filler solutions of higher viscosity, as well as when rapid rates of wall movement were imposed.

In-vitro results

The trends identified in the *in-silico* model were also present in both latex rubber and colonic tissue experiments. Figure 5 shows pressures measured in the centre of the lumen using contents with two viscosities, during diameter reductions similar to the *in-silico* model. All of the features identified in the numerical simulations (Figure 4) were faithfully reproduced in the latex model, demonstrating the validity of the numerical results.

The collated pressure traces results from the sensor immediately underneath the lumen, during a separate series of non-occluding events at different rates of collapse, and with different luminal filler viscosity, for all of the latex rubber contractions are shown in Figure 6. These results demonstrated several key points. Firstly, the wall did not have to make contact with the sensor in order for it to record manometric signals in the presence of a viscous luminal filler. Secondly, there was a clear association between viscosity and pressure: as the viscosity of content increased, the measured pressure increased. Thirdly, as the rate of collapse increased, the rate of rise of recorded pressure also increased, and hence the peak pressure response achieved also increased.

Figure 7 shows equivalent manometric response during non-occluding events in lumen from the rabbit colon, at different rates of wall movement, with fluid content with a viscosity of 880 mPa.s. Despite evident visco-elastic creep of the natural tissue, the similar results to those obtained with latex are evident. The recorded pressure increased with both increasing rate of contraction, and with increasing viscosity of the luminal content.

Due to the visco-elastic creep causing variability in the measured responses, repeated measurements were on one section of gut, using two fillers of different viscosity (880 and 1760 mPa.s). Figure 8 shows this data from 48 separate contractions. The trend lines for both fillers demonstrated a linear increase in the measured pressure measured by the sensor with respect to the applied pressure ($p<0.0001$ for non-zero slope), of 0.48 (95%CI: 0.33-0.62) for the 880 mPa.s filler, and 0.71 (95%CI: 0.64-0.78) for the 1760 mPa.s filler. The higher measured pressures recorded with more viscous filler solutions further confirmed the relationships demonstrated in Figure 6 for low rates of luminal collapse. With lower viscosity filler the data was more scattered ($R2=0.62$ compared to $R2=0.96$ for the

higher viscosity), reflecting more variability in the rate of wall movement, probably caused by the low resistance to collapse of the luminal wall.

Discussion

This joint numerical and experimental study investigated the relationships between pressure changes measured by a manometric sensor, rate of wall movement, and viscosity of luminal content. Close agreement was shown between the *in-silico* and *in-vitro* results, demonstrating the validity of the numerical model within its stated assumptions.

Previous reports have suggested that colonic manometry fails to record non-lumen occluding contractions 4 and that the majority of contractile activity may not be detected in the regions of the colon with large diameters 5. Our results unequivocally demonstrate that manometric devices can respond to non-occluding contractions, and furthermore, that the magnitude of the response is directly dependent on both the viscosity of the contents and on the rate of movement of the luminal wall. Hence, the assumption that non-occluding contractions cannot be recorded by manometry is erroneous.

An influential study by von der Ohr et al concluded that that when the colon exceeds a diameter of 5.6 cm, manometry may miss up to 70% of the contractile activity 5. Our results indicate that luminal diameter in isolation is not an appropriate surrogate measure of the efficacy of intraluminal manometry; the viscosity of the contents and the rate of wall movement will have major effects on the measured pressure. Hence, the colonic diameter inferred by the isobaric inflation of a balloon, as performed by von der Ohr et al, should not be used to delineate between effective and non-effective manometry. It should be further noted that an ‘effective colonic diameter’ defined by the volume of a barostat bag under a pre-described pressure 5 is not comparable to the true colonic condition of a full lumen of the same diameter. Rather, the approach of von der Ohr et al 5 instead offers an indication of the compliance, or resistance to distension, under the action of the expanding bag. Hence it needs to be recognized that the 5.6 cm “colonic diameter” described in that study as the cut-off for effective manometry is highly unlikely to represent the natural working state of the colon. Under normal conditions, once the barostat is removed,

the colonic lumen will return to its normal state in which it is filled with content ranging from gas to semi-solid.

A further point to consider in interpreting the findings of 5 is their assumption about the distances over which contractions propagate in the human colon. At the time of writing their paper, studies in canine colon 15 and human colon 16 suggested that the majority of propagating contractions propagate over distances greater than >10 cm. Thus, they argued that most events detected by a barostat bag (10 cm in length) would reasonably be expected to be detected by neighbouring manometry sensors proximally and distally. However, recent in-vivo, high resolution manometry studies in human colon, with sensors spaced at 1cm intervals, have shown that many colonic propagating sequences are of short extent (3-7 cm) 17. Therefore, events recorded by the barostat would not necessarily have propagated to the manometry sensors. In addition, the barostat bag itself may have stimulated low threshold mucosal afferents, causing localised contractile events that would similarly not necessarily propagate to neighbouring manometry sensors.

The present study shows that viscosity of luminal content has a major influence on the manometric signal. Manometric signals are often recorded in a prepared (empty) colon 18; however the current study suggests that the amplitude of recorded signals are likely to change as the colon fills, simply because of changes in mechanical coupling between wall movements and the pressure sensors. This observation may be relevant to the results of studies in which manometry catheters were placed during colonoscopy in a prepared bowel, followed by recordings over and beyond the following 24 hours. The viscosity of colonic content can vary by many orders of magnitude as it traverses progresses from the caecum to rectum, undergoing the normal de-watering processes. Variation in the amplitude of the manometric signal in different regions of the colon may reflect the nature of the content more than the force of contraction of the muscular wall. For example, in studies performed by some of the present authors 19, 20, the average amplitude of propagating pressure waves in the distal colon was reported to be greater than in the ascending and transverse colon. This was interpreted as reflecting an adaptation of the distal colon to generate stronger contractions required to shift the increasingly viscous content. However, the present current study, together with a recently published numerical consideration of colonic motility 21, suggests that the differing amplitude of the signal may in fact

simply reflect the manometric response changing due to the increasing viscosity of content.

These findings may also have significant implications for the definition of high amplitude propagating pressure waves. These events have been defined under a variety of names and have been defined with cut-off amplitudes ranging from 50 to 136 mmHg 22. The current study suggests that attributing an exact, arbitrary value to distinguish high amplitude events, as some of the authors here have also done in the past (e.g. >116mmHg 19), is inappropriate. However, by no means does this suggest that identification of these events is unimportant, because these events are known to be associated with defecation 23, 24 and luminal propulsion 25 and pathophysiologically, their frequency incidence is diminished in patients with slow transit constipation 18, 26-28.

Gathering direct evidence of our findings from *in vivo* human colonic manometry studies is not easily done, because of the need to dynamically measure intra-luminal pressure and image the luminal dimensions. The latter measurement can be achieved with videofluoroscopy, however as the colonic contractile activity is not under voluntary control, prolonged screening may be required to capture the required events, and that poses ethical concerns. However, evidence is available from analyses of swallowing using videoflouroscopy combined with manometry. These studies readily pick up the intrabolus pressure as a liquid bolus passes a given manometry sensor and then a significantly higher peak as the lumen collapses down on the catheter during the peristaltic squeeze 9.

Although not a focus of this study, the nature of the manometric signal is also likely to be influenced by physical features of the colonic lumen, for example, the presence of constrictions and/or sphincters such as the ileocaecal junction, the colonic haustral folds, sharp angulations (eg: the splenic flexure and sigmoid colon), distal inhibitory neural reflexes acting on the smooth muscle, overall muscle wall hypertrophy (as occurs in diverticulosis), or focal narrowing and/or strictures. Such anatomical features will modify the resistance to longitudinal propulsion of content in response to a localized contraction, and hence will affect the ‘back pressure’ detected by the manometry sensor. The design of our pressure vessel allows for the addition of non-local constrictions at a distance to the imposed wall movements and will be used for future characterisation of the magnitude of such effects.

In conclusion, this study has presented a joint numerical and experimental investigation into the effects of non-lumen-occluding contractions in the presence of viscous media on manometry. Through a series of controlled *in-vitro* experiments using localized imposed wall movements in sections of excised animal gut and latex tubing, and an associated numerical study, we have demonstrated unequivocally that non-occluding luminal contractions are recorded using intraluminal manometry. Our results further demonstrate that the strength of the recorded signal is dependent on both the viscosity of the luminal content and the rate of contraction of the luminal wall. As pointed out above, the compliance and diameters of neighbouring regions of gut are also likely to be important factors, although these were not included in the present study.

While we have related this study to the specific conditions facing the researcher undertaking colonic manometry, the results described here are equally applicable to other regions of the GI tract in which viscosity of content is either intentionally varied (such as controlled swallows in the oesophagus) or naturally occurs (such as chyme entering the small bowel following meals of differing consistency and content).

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The work was conceived and planned during a meeting between JA, PD, IC, GOG, AP, NS, MC, SB and MC. The experimental protocol was developed by JA, AP and SB. The catheters were fabricated and supplied by JA and the in-vitro testing environments were devised by MC and NS and assembled by NB and SM. The experiments were conducted by AD under the supervision of JA and PD, and the numerical model was assembled and run by JL under the supervision of RA, GOG and AP. The draft was prepared by JA and edited by all authors.

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Figures:

1. Geometry of the COMSOL numerical model used to calculate the effect of localised wall movements on pressure recorded on an underlying manometric sensor located in the centre of the region of applied wall movement.

2. Schematic of the setup used to generate the localized movement of the wall of a tubular segment of gut or latex. A fluid-filled syringe is used to hydraulically

generate the required localized reductions in diameter (monitored by a pressure gauge). This causes the walls of the specimen of gut to move inwards, towards the manometric catheter, in a controlled rate. The gut is filled with a solution of known viscosity (dark blue), from the two reservoirs (dark blue).

3. Determination of the point of occlusion. A graded series of pressure steps were applied to determine that point where the wall of the tube contacted the pressure sensor on the manometric catheter. At this point, the signal recorded by the manometric sensor starts to increase rapidly. For the rest of the study, pressures were used that were less than 80% of the threshold required for lumen occlusion.
4. Modelling of sensor recordings during wall movements imposed by increasing pressure in the chamber surrounding the gut. The applied pressure is shown in blue, and calculated sensor responses are shown for viscosities of 780 and 5000 mPa.s (red and purple traces).
5. Measured changes in pressure on the axis of the latex lumen for phasic applied pressure profiles, using luminal content with viscosities of 795 and 3180 mPa.s (blue and red traces).
6. Effects of viscosity of filler on initial pressure gradients of measured pressures recorded from the sensor immediately underneath the region of contraction during collapse of the latex lumen.
7. Measured changes in pressure on the axis of the section of rabbit colon lumen for phasic applied pressure profiles, using luminal content with a viscosity of 880 mPa.s.
8. Measured rate as a function of applied rate for 48 separate contractions using filler viscosities of 880mPa.s and 1760mPa.s. Linear curve fits to the data gives slopes of 0.48 (R^2=0.62) and 0.71 (R^2=0.96) respectively.

Supporting Information

The COMSOL *in-silico* model was solved in two coupled steps. First, a pressure load was applied to the tube wall (as indicated by the dashed arrows in Figure 1) and the resulting wall deformation was solved, assuming linear-elasticity of the wall material. Next, the response of the luminal fluid to the pressure exerted by the deforming wall

was solved using the Navier-Stokes formulation. Fluid pressure at the centre of the tube was computed. This corresponds to the position of the central pressure sensor on the recording catheter.

COMSOL's moving mesh Arbitrary Lagrangian-Eulerian application (ALE) was used to couple the forces from the deforming tube wall onto the fluid interface. This intermediate step generated a deformed mesh of the fluid subdomain at each time-step taken by the solid mechanics solver, which was then input into the fluids solver.

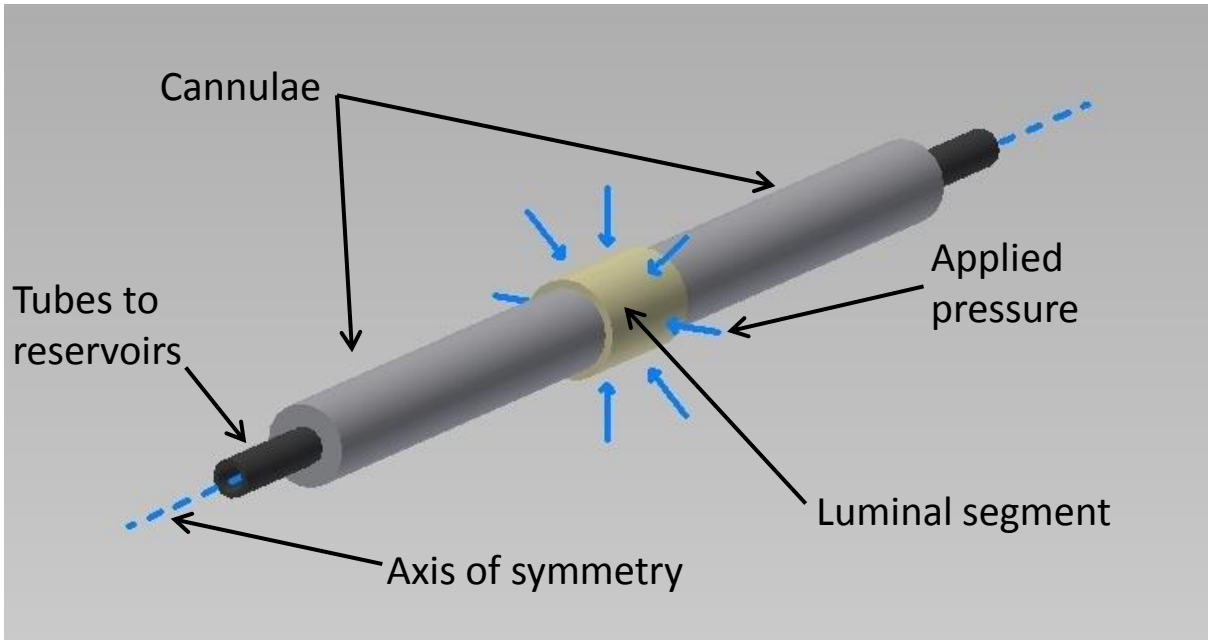

Figure 1. Geometry of the COMSOL numerical model used to calculate the effect of localised wall movements on pressure recorded by a manometric sensor located on the axis of the lumen. The model assumes cylindrical symmetry with a larger diameter representing the cannulae and lumen and small diameter tubes representing non-local constrictions. The contractile region of the lumen was located at the mid-point of the lumen. This simplified geometry matched the functional design of the experimental apparatus as shown by the dashed lines in Figure 2.

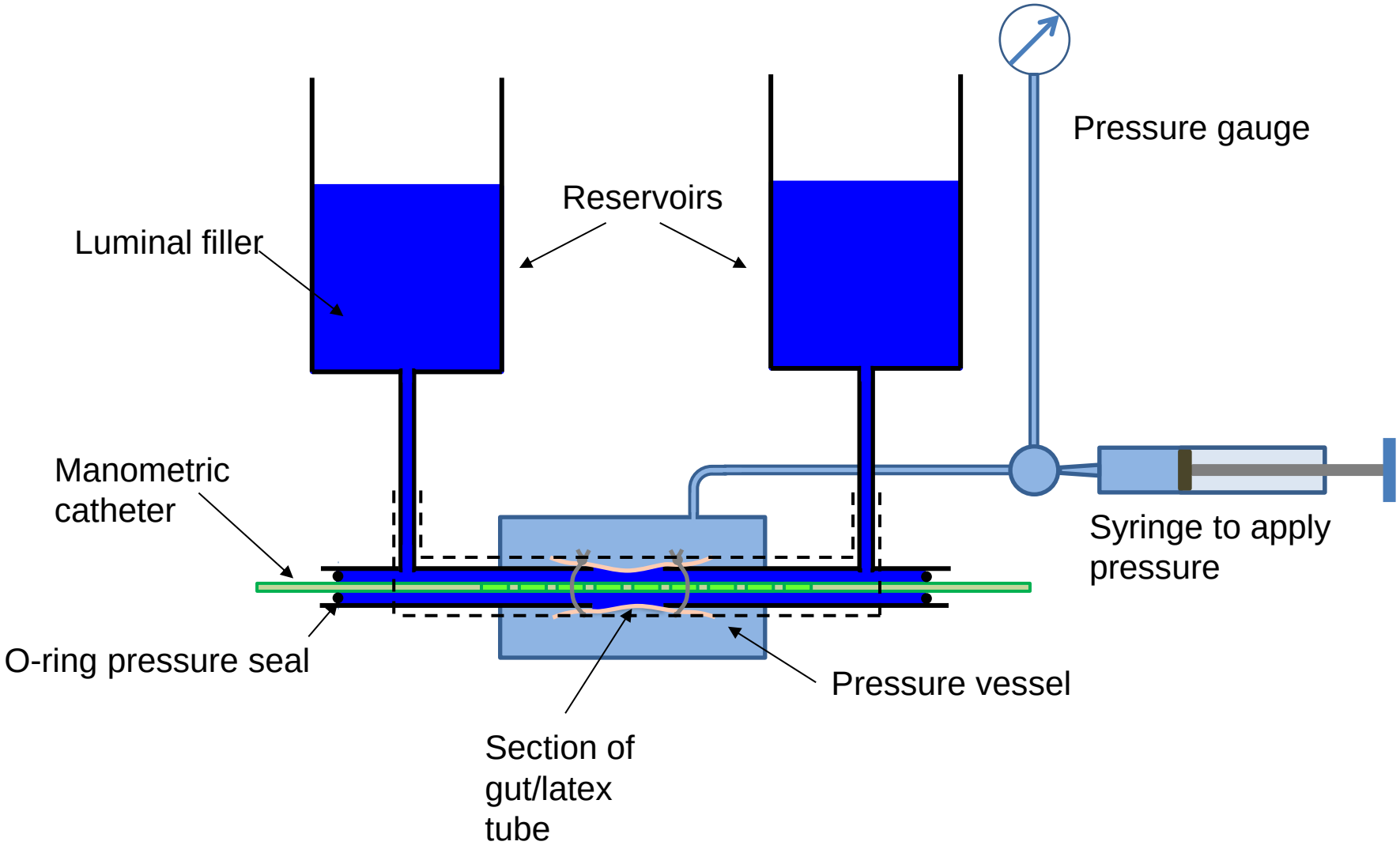

Figure 2. Schematic of the setup used to generate the localized movement of the wall of a tubular segment of gut or latex. A fluid-filled syringe is used to hydraulically generate the required localized reductions in diameter (monitored by a pressure gauge). This causes the walls of the specimen of gut to move inwards, towards the manometric catheter, in a controlled rate. The gut is filled with a solution of known viscosity (dark blue), from the two reservoirs (dark blue). The region of the apparatus simulated by the in-silico model is indicated by the dashed lines.

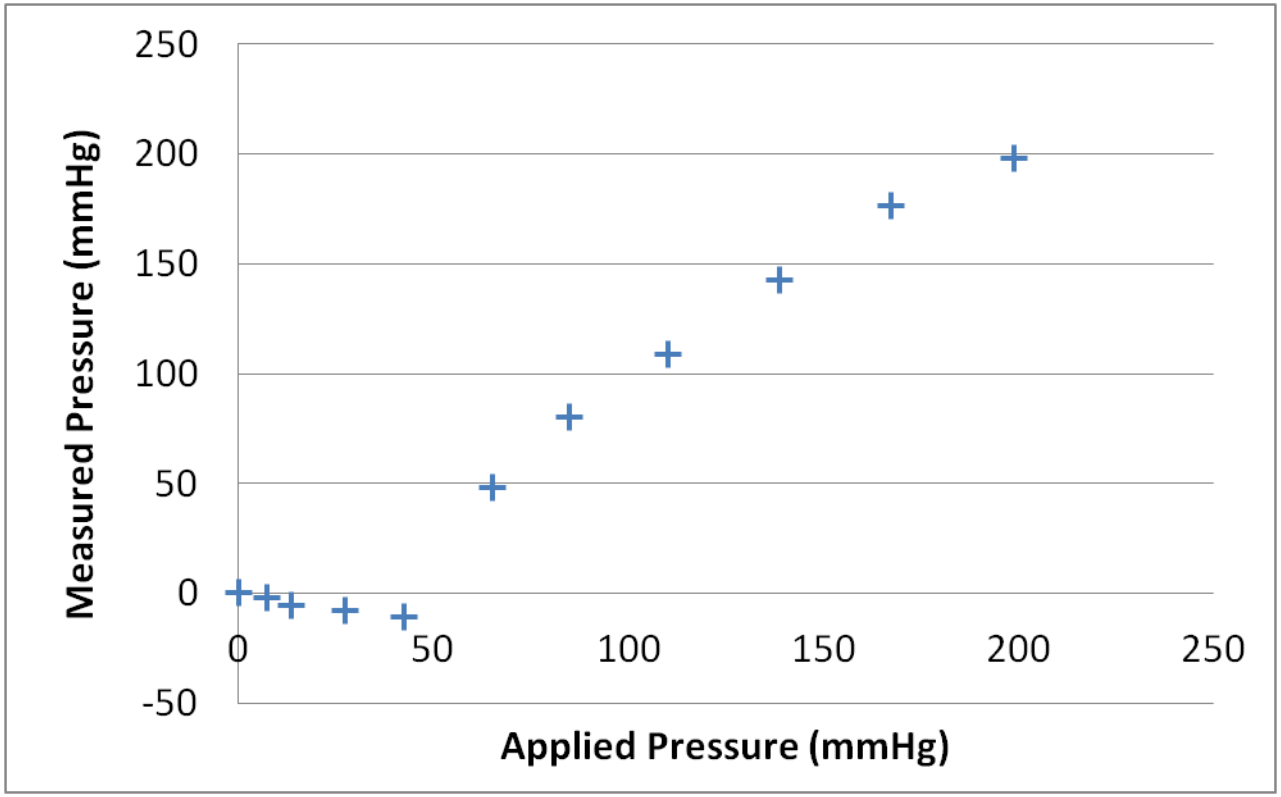

Figure 3. Determination of the point of occlusion. A graded series of pressure steps were applied to determine that point where the wall of the tube contacted the pressure sensor on the manometric catheter. At this point, the signal recorded by the manometric sensor starts to increase rapidly. For the rest of the study, pressures were used that were less than 80% of the threshold required for lumen occlusion.

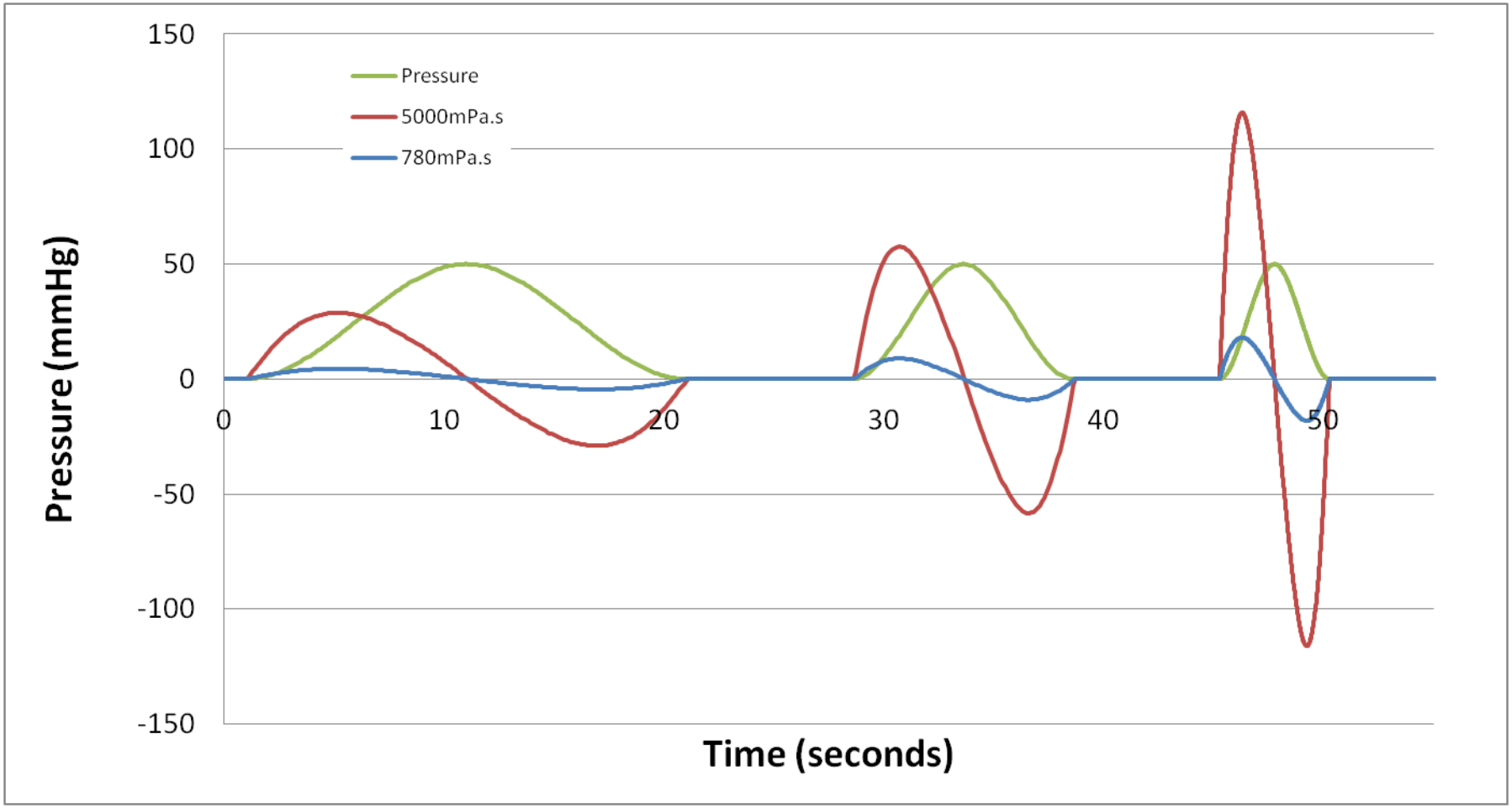

Figure 4: Modelling of sensor recordings during wall movements imposed by increasing pressure in the chamber surrounding the gut. The applied pressure is shown in green, and calculated sensor responses are shown for viscosities of 780 and 5000 mPa.s (blue and red traces).

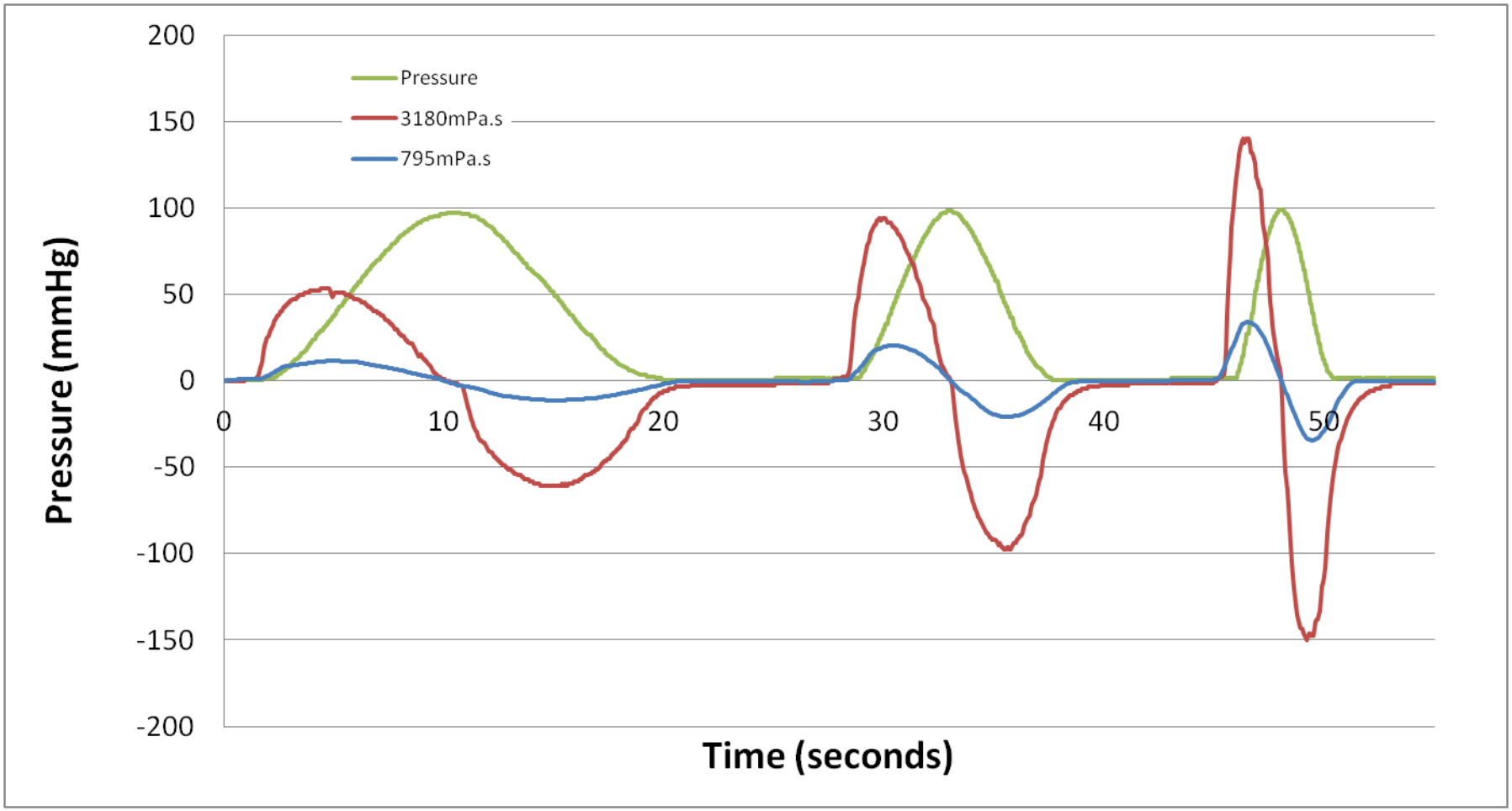

Figure 5: Measured changes in pressure on the axis of the latex lumen for phasic applied pressure profiles(green trace) , using luminal content with viscosities of 795 and 3180 mPa.s (blue and red traces).

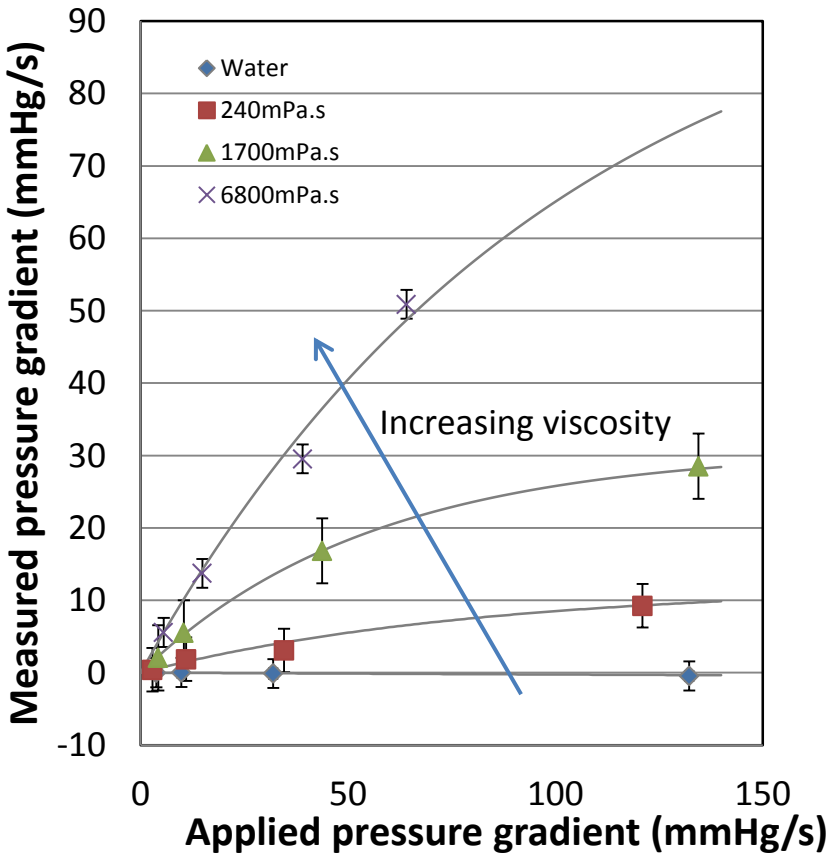

Figure 6: Effects of viscosity of filler on initial pressure gradients of measured pressures recorded from the sensor immediately underneath the region of reducing diameter during collapse of the latex lumen

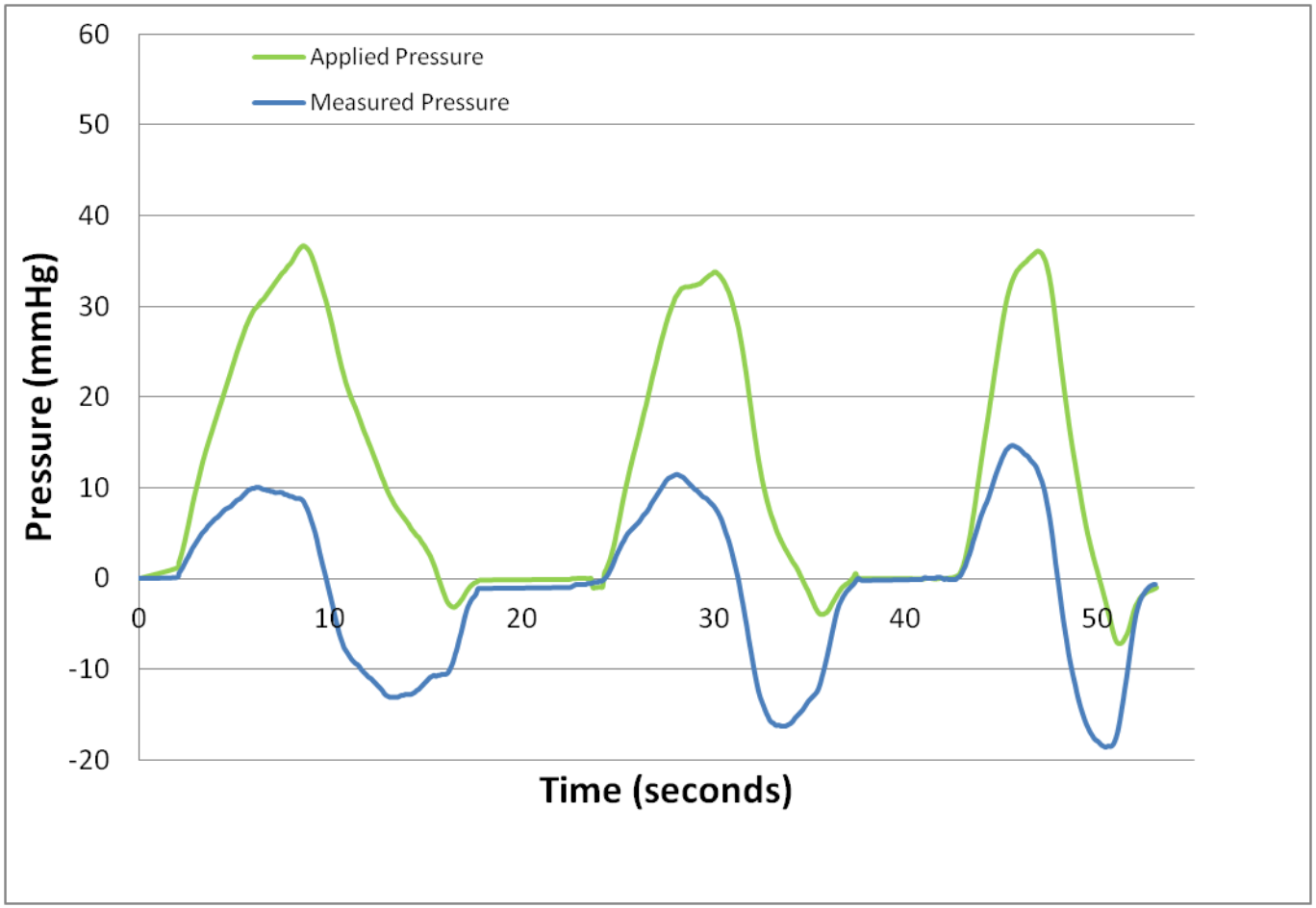

Figure 7: Measured changes in pressure on the axis of the section of rabbit colon lumen for phasic applied pressure profiles, using luminal content with a viscosity of 880 mPa.s.

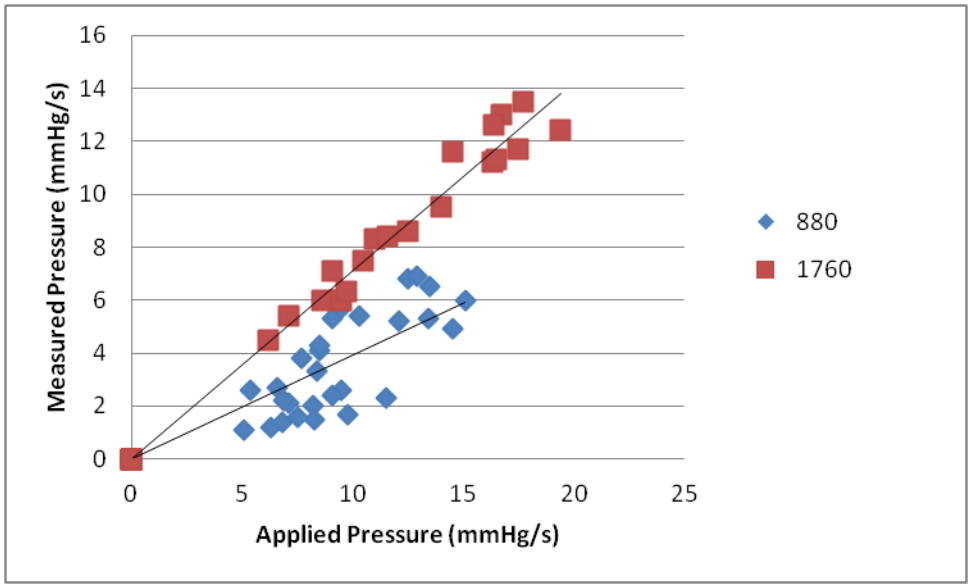

Figure 8. Measured rate as a function of applied rate for 48 separate contractions using filler viscosities of 880mPa.s and 1760mPa.s. Linear curve fits to the data gives slopes of 0.48 (R^2=0.62) and 0.71 (R^2=0.96) respectively.