Influence of Looped Colonoscope on Deformation of Intestinal Wall in Colonoscopy

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Abstract

Colonoscopy that is a very commonly carried out procedure has several problems, including a risk of perforation of the colon and significant discomfort for patients. Loop formation can be the reason of these problems. Loop formation is further associated with the configuration of the colon, in particular the rectum-sigmoid and sigmoid-descending segments that have a small curvature and “S”-shaped profiles where the looped colonoscope exerts a quasi-static force on intestinal wall, and then results in deformation of the intestinal wall. Variable-stiffness colonoscope and over-tube colonoscope may be used to prevent loop formation; however, conflicting results relating to their use have been reported. In this paper, influence of a looped colonoscope on deformation of the intestinal wall is analyzed. It was found that the flexural rigidity of the looped colonoscope contributes deformation of the intestinal wall.

Keywords: Colonoscope, Intestinal wall, Flexural rigidity, Frictional force, Loop formation

1. Introduction

Colonoscopy is a very commonly carried out procedure and remains the most effective screening tool against colorectal cancer. Not only is it a useful screening and diagnostic tool, but it also facilitates the removal of premalignant polyps. Colonoscopy that is done on patients a very redundant sigmoid colon. Other patients have a transverse colon that makes an M shape, and dips down into the pelvis. The generally round shape of the colon means that after a couple of turns, and the formation of a semicircle in the scope, further advancements risk making a larger looping, while the tip of the scope itself does not advance at all. In some cases, the looping takes the shape of an alpha, thus the name “Alpha looping” or “N” looping [1,2].

Loop formation is related to geometrical “S” configuration of the sigmoid colon and the flexible colonoscope [3].

Some approaches to preventing loop formation have been proposed, such as variable-stiffness colonoscope and over-tube colonoscope. However, these instruments have some problems, including risk of perforation and significant discomfort for patients. The reason of these problems could be that the looped scope exerts a quasi-static force on the intestinal wall, and then results in deformation of intestinal wall. However, influence of a looped colonoscope on deformation of intestinal wall has not been closely studied. In this paper, effects of a looped colonoscope on deformation of the intestinal wall will be studied.

2. Effect of a looped scope on deformation of intestinal wall

2.1 Frictional force acting on intestinal wall

The rectum-sigmoid and sigmoid-descending segments have small curvatures with an “S”-shaped profile. The looped scope exerts quasi-static forces on the intestinal wall. As the colonoscope is pushed, quasi-static force becomes frictional force. This study examines the quasi-static force for given shape of a looped scope, and then derives the frictional force equation.

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Choi [4] analyzed an endoscope’s elastics in an exoskeleton structure, and derived the following equation for distributed force along the segment of a stem based on Plaut’s work [5-8]:

\[ D = EI \left( \frac{d^2 \theta}{d \ell^2} + \frac{1}{2R} \right) \]

where \( N(l) \) is the normal force at position \( l \), \( D \) is the distributed force on \( dl \) that is an infinitesimal length of the stem, \( \theta \) is an infinitesimal angle along \( dl \) at the center of radius or curvature, and \( EI \) is the flexural rigidity of the stem.

A looped colonoscope introduces a distributed force on the inner surface of the colon. This study reverses the problem to find the quasi-static force on inner wall of the colon exerted by a looped colonoscope. The looped colonoscope through the rectum up to the descending colon exhibits an “S” configuration. To simplify Eq. (1), a quadrant shape of a looped colonoscope is studied, as shown in Fig. 1 [4]. The corresponding boundary conditions are applied to Eq. (1). In the following, the parameters are defined:

- **Q**: quasi-static force
- **S**: given length of the colonoscope
- **r**: radius of curvature of looped colonoscope

Evaluating boundary conditions of \( N = 0 \) and \( dl = r d \theta \) leads to

\[ D = EI \left( \frac{d^2 \theta}{d \ell^2} + \frac{1}{2R} \right) \]

Eq. (2) can be integrated by using three conditions. The derivation of Eq. (3) is given in the Appendix.

\[ D = EI \left( \frac{6 \theta}{S^2} + \frac{1}{2R^2} \right) \]

Then, leading to

\[ Q = EI \left( \frac{6 \theta}{S^2} + \frac{S}{2R^2} \right) \]

\[ S = r \theta \]

Therefore, frictional force \( F_I \) induced by the quasi-static force is responsible for the elongation of the intestinal wall:

\[ F_I = \frac{6EI}{r} \left( \frac{12 \theta^2}{2R} + \frac{1}{2R} \right) \]

where \( \mu \) is frictional coefficient; \( \theta \) is a function of length \( l \). When angle \( \theta \) reaches zero, the corresponding length of the looped scope reaches zero, and thus there is the singularity in Eq. (6). In this case, the quasi-static force would approach infinity. However, the quadrant configuration of the looped colonoscope has a constant radius \( r \), which implies that it is impossible to make a quadrant configuration of the looped colonoscope with a quasi-static force towards the center point of the quadrant [4].

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**2.2 Physical properties of intestinal tissues**

The properties of intestinal tissues were studied by Dario et al. [9]. The stress-strain relationship can be approximated as:

\[
\begin{align*}
\sigma_x &= b_x \varepsilon_x^2 + d_x \varepsilon_x^3 \\
\sigma_z &= b_z \varepsilon_z^2 + d_z \varepsilon_z^3
\end{align*}
\]

where \( \sigma_x \) represents the intestinal lagrangian stress along the radius of intestinal tissue, \( \sigma_z \) represents the intestinal stress along its length direction, \( \varepsilon_x \) represents the circumferential strain of intestinal tissue, and \( \varepsilon_z \) represents strain along its length. The other parameters are dimensional coefficients to be determined through experiment.

The radial strain is very small, thus, \( \sigma_z \) is negligible. The relationships between stress and strain for the mesentery are:

\[
\begin{align*}
\sigma_m &= b_m \varepsilon_m^2 + d_m \varepsilon_m^3 \\
\sigma_m &= b_m \varepsilon_m^2 + d_m \varepsilon_m^3
\end{align*}
\]

where \( \sigma_m \) and \( \varepsilon_m \) represent the mesentery lagrangian stress and strain along its length, respectively, and \( \sigma_m \) and \( \varepsilon_m \) represent the mesentery stress and strain along its height, respectively. The other parameters are dimensional coefficients to be determined through experiment.

**2.3 Deformation equation of intestinal wall**

The frictional force is responsible for deformation along the intestinal wall length. The frictional force induced by a quasi-static force exerted by the looped colonoscope resists the advancement of the colonoscope. The sigmoid colon surrounding its mesentery is attached to the intestinal wall, and thus there is the same elongating amount with intestinal wall. An analysis of the frictional force acting on the intestinal wall and its surroundings is shown in Fig. 2. The corresponding equation is:

\[
\begin{align*}
F_I &= \sigma_z t_s d_s + \sigma_m t_m h \\
\varepsilon_m &= \varepsilon_m - \Delta S/S
\end{align*}
\]

where \( t_s \) is the thickness of the intestine, \( t_m \) is the thickness of the mesentery, \( d_s \) is the diameter of the colon, \( h \) is the mesenteric transversal length, \( S \) is a given length of the looped colonoscope.
colonoscope, and $\Delta S$ is the deformation (displacement) of the intestinal wall.

Integrating Eq. (5), (6), (7), (8), and (9) leads to

$$b_x (\Delta S/r\theta)^2 + d_m (\Delta S/r\theta) \pi d_t + b_m (\Delta S/r\theta)^2 +$$

$$d_m (\Delta S/r\theta) l_s h = \frac{\mu EI}{r^2} \left( \frac{12 + \theta^2}{2\theta} \right)$$

Eq. (10) gives the deformation of the intestinal wall and its surrounding mesentery, which is a function of the flexural rigidity of the insertion tube, the curvature radius of looping, and the corresponding angle of curvature of the looping.

![Diagram](image)

Figure 2. Analysis of force along intestinal wall length direction.

3. Experimental determination of flexural rigidity of the scope

Flexural rigidity of the colonoscope is important parameter in Eq. (10). The flexural rigidity of an actual colonoscope was thus investigated to study its influence on using Eq. (10) quantitatively. A single-column testing machine (Model-3366, Instron, Norwood, MA) was used to test an Olympus™ CF-Q160L colonoscope. The testing of the insertion tube of the colonoscope flexural rigidity was performed with the assumption that the colonoscope can be treated as a beam [10]. The test span of the colonoscope was treated as a simple beam supported by two rollers. A displacement $\delta$ was imposed at the mid-span and the corresponding load $P$ was measured. The flexural rigidity $EI$ was calculated as [11,12];

$$EI = \frac{PL^3}{48\delta}$$

(11)

where $L$ is the span (120mm).

The results of each test were analysed and assessed for linearity using least-squares regression. A pin load 51 cm away from the distal end on the fixture is shown in Fig. 3. From a linear regression analysis of the loading segment data, the slope was 1.023 and $R^2 = 99.3\%$. This indicates that the data is appropriately linear for the determination of EI.

![Graph](image)

Figure 3. Flexural load-deflection curve on the spot 51 cm from the distal end of the scope.

Fourteen intervals from the 210-cm mark on the insertion tube to the 1510-mm mark were tested. A total of 14 spots along the insertion tube were tested. The flexural rigidity with 95% confidence interval bars is shown in Fig. 4. The location factor for the flexural rigidity of the insertion tube is significant.

![Graph](image)

Figure 4. Flexural rigidity with 95% confidence interval bars for the CF-Q160L colonoscope.

The looped scope effect on its flexural rigidity was tested. Fig. 5 shows the flexural rigidity of the scope conducted with and without looping. The results show that no looping and a looping have different flexural rigidities for the Olympus CF-Q160L colonoscope. In general, the range of CF-Q160L colonoscope’s flexural rigidity is between 200 N·cm² and 700 N·cm² under all circumstances.

4. Results and discussion

Eq. (10) was used to analyze the influence of the physical properties of the insertion tube on the intestinal wall during colonoscopy. It quantifies elongation of the intestinal wall and its surrounding mesentery corresponding to given conditions with respect to flexural rigidity. In Eq. (10), deformation
Figure 5. Mean EI value of the CF-Q160L colonoscope with and without a loop configuration.

(elongation) is proportional to the flexural rigidity (EI) of the colonoscope and also changes with the curvature radius of looping. Cheng et al. [2] quantified and analyzed the deformation of the colon with considering external force/torque, but the influence of the flexural rigidity of the insertion tube on the deformation of the intestinal wall was not considered. Therefore, influence of a looped colonoscope on looping will be further analyzed based on his working.

The configuration of the looped insertion tube was determined from the segment of the rectum-sigmoid colon (i.e., curvature radius of rectum-sigmoid colon \( r_{\text{rectum-sigmoid}} \) and corresponding angle \( \theta_{\text{rectum-sigmoid}} \)) according to Eq. (10). The physical properties of the intestinal wall and its surrounding were obtained from the literature [9].

The flexural rigidity (EI) of the insertion tube of the Olympus CF-Q160L colonoscope is affected by the location factor and the looping factor in terms of experiment results, but the mean of EI (400 N·cm²) is used. All data are listed in Table 1.

Table 1. Biomechanical properties and anatomical parameters [13,14].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_r ) (MPa)</td>
<td>4.85</td>
</tr>
<tr>
<td>( d_r ) (MPa)</td>
<td>0.15</td>
</tr>
<tr>
<td>( b_{at} ) (MPa)</td>
<td>0.27</td>
</tr>
<tr>
<td>( d_{at} ) (MPa)</td>
<td>0.06</td>
</tr>
<tr>
<td>( d_r ) (MPa)</td>
<td>3.5</td>
</tr>
<tr>
<td>( h ) (cm)</td>
<td>2.5</td>
</tr>
<tr>
<td>( l_r ) (mm)</td>
<td>7.5</td>
</tr>
<tr>
<td>( l_{at} ) (mm)</td>
<td>5.5</td>
</tr>
<tr>
<td>( r_{\text{rectum-sigmoid}} ) (m)</td>
<td>0.2</td>
</tr>
<tr>
<td>( \theta_{\text{rectum-sigmoid}} ) (rad)</td>
<td>( \pi/4 )</td>
</tr>
<tr>
<td>( \nu )</td>
<td>0.24</td>
</tr>
<tr>
<td>EI (N·cm²)</td>
<td>400</td>
</tr>
</tbody>
</table>

The deformation (elongation) of the intestinal wall due to the insertion tube calculated using Eq. (10) was 0.572 cm. \( \Delta d \) represents the displacement of the scope in the colon; \( \Delta d \) represents elongation of the intestinal wall. When \( \Delta d < \Delta d' \), there is a relative motion between the colonoscope and the colon. When \( \Delta d \geq \Delta d' \), there is no relative motion between the colonoscope and the colon.

During colonoscopy, the looped colonoscope causes a great deal of patient discomfort and perforation of the colon, and can lead to an incomplete colonoscopy. When the colonoscope is stationary, i.e., the tip of the colonoscope itself does not advance, so there is no relative motion, a push on the colonoscope can result in severe injury. Thus, the relative motion between the colon and the colonoscope is very important information for physicians. According to Fig. 6, we found that there is no relative motion between the colonoscope and the colon. The reason is that the influence of the flexural rigidity of the insertion tube of the colonoscope on the intestinal wall is significant. The combination of the colonoscope and the intestinal wall is considered as an elastic rod structure. An elastic structure with increasing load (the pushing force applied by an endoscopist) ultimately becomes unstable. When the load applied exceeds the critical load of this structure, the scope becomes unstable and naturally seeks another stable equilibrium state. According to this analysis, the critical load of an elastic rod is an important parameter for structural stability. The critical load \( F_{cr} \) of the rod model can be determined using Kirchhoff’s equilibrium equation [3]:

\[
F_{cr} = \frac{4\pi^2 EI \cos^3 \vartheta}{L^2 (1 + 3\cos^2 \vartheta)}
\]

(12)

where \( L \) is the length of the rod, \( \vartheta \) is the spiral angle, and \( EI \) is the flexural rigidity of the rod.

Figure 6. Estimated elongation of the intestinal wall versus the given displacement of the colonoscope.

Based on Eq. (12), structural stability with increasing EI is improved. Thus, variable stiffness colonoscope which have built-in variable shaft stiffness to stiffen the insertion tube are used to prevent re-looping formation in colonoscopy. Based on these two aspects, i.e., influence of looped colonoscope on deformation of intestinal wall and critical load of the rod’s structural stability, flexural rigidity of the colonoscope would be compromised. The results of preliminary studies could lead to the redesigning of variable-stiffness colonoscope and future novel colonoscope device.

5. Conclusion

This paper quantitatively investigated the influence of the physical properties of a looped colonoscope on loop formation. The looped colonoscope has a significant impact on
deformation of the intestinal wall in colonoscopy. The flexural rigidity of the insertion tube of the Olympus™ CF-Q160L colonoscope was also investigated. Its flexural rigidity is affected by location factor and the looping factor.

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Appendix

Equation (3) derived as follows:

\[
D = EI \left( \frac{d^2 \theta}{dt^2} + \frac{1}{2r} \right)
\]

(A-1)

Three boundary conditions were applied to integrate Eq. (A-1) in terms of the moment \( M \) and shear force \( \tau \) at the free end of the beam. The following two equations derived from Eq. (1) were used [4]:

\[
\begin{align*}
M &= EI \frac{d \theta}{dt} \\
\tau &= EI \frac{d^2 \theta}{dt^2}
\end{align*}
\]

(A-2)

At the free end of beam \( l_{\text{end}} \), moment \( M \) and shear force \( \tau \) are equal to zero:

\[
\begin{align*}
\frac{d \theta}{dt} |_{l=l_{\text{end}}} &= 0 \\
\frac{d^2 \theta}{dt^2} |_{l=l_{\text{end}}} &= 0
\end{align*}
\]

(A-3)

At the clamped end of beam, \( l = 0 \), so the third boundary condition is \( \theta_{l=0} = 0 \). Integrating (A-1) into the 2nd ordinary differential equation leads to:

\[
\frac{d^2 \theta}{dt^2} = \left( \frac{D}{EI} - \frac{1}{2r} \right) l + c_1
\]

(A-4)

Using boundary condition (A-3) to find the constant

\[ c_1 = -l_{\text{end}} \left( \frac{D}{EI} - \frac{1}{2r} \right) \]

leads to:

\[
\frac{d^2 \theta}{dt^2} = \left( \frac{D}{EI} - \frac{1}{2r} \right) l - l_{\text{end}} \left( \frac{D}{EI} - \frac{1}{2r} \right)
\]

(A-5)

Integrating (A-5) using the other boundary condition yields:

\[
\theta(l) = \left( \frac{l}{6} - l_{\text{end}} \frac{l^2}{2} + l_{\text{end}} \left( \frac{D}{EI} - \frac{1}{2r} \right) \right)
\]

(A-6)

Given length \( S \) of the colonoscope to find disturbed force along \( l \in (0, S) \), let \( l = S \). At the free end of the beam, \( l_{\text{end}} \) is length of the colonoscope. Substituting \( l = S \) and \( l_{\text{end}} = S \) into Eq. (A-6) to find distributed force \( D \) along given length \( S \) of the colonoscope yields:

\[
D = EI \left( \frac{6\theta}{S^2} + \frac{1}{2r} \right)
\]

(A-7)

References
