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Influence of different lubricating fluids on friction trauma of small intestine during enteroscopy

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ABSTRACT

Given the increasing attention to abdominal pain problem caused by small intestine damage during enteroscopy, the development of lubricating fluids for injury prevention has become an urgent task. In this study, in vivo friction experiments were conducted by using rabbit small intestine tissue under natural condition and lubricated conditions of Normal Saline, Calf Serum and Hyaluronic Acid, respectively. A quantitative grading system was designed to assess the friction trauma of the small intestine tissue. Results showed that the Calf Serum or Hyaluronic Acid lubricant could relieve the traumas and reduce the friction at the probe-small intestine mucosa interface. These results can be useful to identify the suitable lubricating fluids for the safe operation of enteroscopy.

1. Introduction

Enteroscopy is widely available in mucosal visualization, tissue sampling and therapeutic intervention in the small intestine [1]. It has the main advantages of short investigating time, full control over the device and repetitive pathology visualization [2]. In order to improve the operating efficiency and shorten operating time, excessive push force is often applied during enteroscope interting into the sinuous intestinal tract, which can cause intestinal damage due to the lack of haptic feedback system on the enteroscope device [2,3]. Moreover, the front end of commercial available endoscope is wrapped in a cylindrical rigid tube with 4–10 mm long [4]. The tube is usually produced by a metallic material such as stainless steel or shape memory alloy [5,6]. In order to comply with the general requirements for medical endoscopes and accessories [7], the tube has a smooth surface with low surface roughness and curved edges with small radius of curvature. However, the hard front and sharp edges of the endoscope usually bruise the intestinal tissue. The appearance of damage may be a main precipitating factor of postoperative complications after intervention [2,3]. Minor complications of enteroscopy usually include nausea, vomiting, abdominal distension as well as abdominal pain, while major complications include perforation, pancreatitis, bleeding as well as aspiration pneumonia [2,3]. Xin et al. reported that the rate of the minor complications was 9.1% by counting the 2017 cases and the rate of the major complications was 0.72% for the 9047 cases [3]. Moreover, the rate of the abdominal pain was 93.8% for the 100 cases of a Chinese hospital [8]. Therefore, preventing small intestine damage is critical for safe operation of enteroscopy.

To relieve tissue or organ damage, adding lubricating fluid at the tissue-endoscope interface is a simple, accessible and economic way during endoscopy examination [9]. The traditional lubricating method is to apply a lubricant such as lignocaine gel or chlorhexidine gel to the surface of endoscope before inserting into the intestinal tract [9,10]. However, the lubricant is easily rubbed off due to the excessive extrusion force and friction resistance between the instrument and tissue surface during entry, which in turn causes the poor lubrication [11]. In order to solve the above problem, Brocchi et al. developed a new method to gradually inject a lubricant from the front end of the endoscope during endoscopy examination [12]. According to this approach, some studies confirmed that coating warm water on the surface of colon mucosa was helpful to attenuate patient discomfort and pain during colonoscopy [13–17]. This method has been used in clinic [9,18,19]. However, as far as the authors know, whether the above technique is effective in enteroscopy has not been mentioned. Besides, little current data has been available to give advice on the selection of lubricants that can helpful to relieve small intestine damage during enteroscopy.

On the studies of friction between endoscopic device and the inner wall of small intestine, He et al. studied the frictional resistance between Expanding-Extending Robotic Endoscope and pig small intestine, and found that the tangential force ranged from 0.1 N to 0.4 N [20]. Kim et al. investigated the friction characteristics of capsule endoscope moving inside the pig small intestine [21]. Results revealed that the friction coefficient increased with increasing moving speed and decreased with increasing normal load [21]. Terry et al. characterized the

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adhesivity between the mucosa of porcine small intestine and Robotic capsule endoscope materials, and found that the mean tack strength and the mean peel strength were $0.198 \pm 0.070\,mJ/cm^2$ and $0.055 \pm 0.016\,mJ/cm^2$, respectively [22]. Wang et al. also showed that the frictional resistance between specially designed capsule prototypes and porcine small intestine rose with increasing moving speed [23–25]. Moreover, some researches focused on the effects of material or surface contour of the capsule on the friction characteristics of small intestine mucosa. Baek et al. found that a smooth cylindrical capsule showed the least frictional resistance [26]. Lyle et al. revealed that micro-patterned polydimethylsiloxane yielded a significantly higher friction coefficient than stainless steel or polycarbonate [27,28]. Wang and Yan showed that the nominal friction coefficient continuously decreased when the surface contour changed in the order of triangular, rectangular, cylindrical and plane [29]. Zhang et al. also indicated that the friction coefficient greatly depended on the different diameters of surface micropillar arrays [30]. Besides, research works about the influences of lubricating fluids on the friction characteristics and damage responses of small intestine mucosa are still extremely limited.

In general, most studies focused on the influence of lubricants on the complications after colonoscopy based on the improved lubricating method [13–17]. However, the data related to the mechanical characteristic and trauma response at the endoscope-soft tissue interface is still limited. Therefore, the aim of this research was to study the effect of lubricating fluids on the mechanical characteristics and trauma responses of small intestine during enteroscopy, and to determine the effectiveness of these lubricating fluids. Based on the improved lubricating method mentioned by Brocchi et al. [12], the friction characteristics and trauma responses of in vivo small intestines were investigated under natural condition and lubricated conditions. The degree of small intestine trauma was determined according to an original quantitative grading system. The results not only can be useful to identify the suitable lubricating fluids for the safe operation of enteroscopy, but also can provide the basic data for the development of the new lubricating approach in enteroscopy.

2. Materials and methods

2.1. Specimen preparation

In vivo animal experiments were performed on an anesthetized rabbit model. The rabbits were studied with the approval of Institution Animal Care and Use Committee, China. All the experiments were conducted in compliance with regulations for the Administration of Affairs concerning Experimental Animals, China. Three New Zealand adult male rabbits with the mean weight of 2.0 ± 0.4 kg were supplied by Experimental Animal Culture Center, Sichuan province, China. Two rabbits were used for the in vivo friction experiments and one rabbit was used for the wettability determination. All these animals were placed on a water-only diet starting 24 h prior to surgery to reduce the amount of food debris in the gastrointestinal tract. According to the methods in our previous studies [31,32], the rabbits were anesthetized and fixed. After hair removal and cleaning, an incision was made along the rabbit abdominal longitudinal. Then the small intestine was slightly pulled out in vivo and cut open along the longitudinal axis to expose the mucosal surface for the friction experiment (Fig. 1 (b)), which would be done according to the friction coefficient measurement method for porcine small intestine [28]. Moreover, fifteen sections of small intestine tissues (about 4 cm long) were taken for the wettability determination of small intestine mucosa under lubricated conditions.

The lubricating fluids were 0.9% NS (Normal Saline), 0.9% CS (Calf Serum) and 1% HA (Hyaluronic Acid), which were chosen as lubricating fluids since they had good biocompatibility and were often used in clinic [33–37]. The densities of these fluids were 0.986 ± 0.045 g/ml, 1.000 ± 0.035 g/ml and 0.947 ± 0.078 g/ml, respectively.

2.2. Friction tests

To simulate the small intestine-enteroscope interface, friction experiments were carried out in a ball-on-flat configuration by using a UMT-II series multi-specimen Biomedical Micro-Tribometer (UMT-II, CETR Corporation, America), as shown in Fig. 1 (a) and (c). The UMT-II was a computer-controlled benchtop instrument, which was adapted to measure tribological parameters. The counterpart was a semi-spherical probe (R 2.5 mm) to simulate the front end of the enteroscope. The probe was made of the same medical stainless steel material as the tube of the front end of the enteroscope. Its surface roughness was about 0.155 μm, which was basically the same as the tube of the enteroscope. It was attached to a suspension system of the UMT-II. The medical tray with the anesthesia rabbit was placed on the bottom of the instrument. The dissected small intestine tissue of the anesthesia rabbit was pulled out and placed freely on the test bench of the UMT-II (Fig. 1 (b)). Before testing, the surface of small intestine mucosa was slightly cleaned by using some absorbent cotton to remove excess moisture and impurities. Then the lubricating fluid with the volume of 1 ml was gentle evenly coated on the 10×10 mm tested part by using a 2 ml syringe.

According to the statistical results described in the previous studies [38,39], the average value of loading force of endoscope was less than 0.34 N, and the movement speed of endoscope was usually no more than 10 mm/s. Thus, taking into account the vulnerable characteristics of the measured tissue, the stainless steel probe pressed on the inner wall of the small intestine under the programmed normal force of 0.2 N and then moved linearly with the constant speed of 0.05 mm/s (Fig. 1c) to simulate the insertion operation during the enteroscopy. The sliding displacement D was 5 mm. Selecting these parameters was also recommended by two professional surgeons. Moreover, small intestine tissues were also tested under natural condition (without lubricating fluid) for comparison. The experiments were performed with five replications under the same lubricated condition. All the tissues were tested at a normal room temperature of $20 \pm 3\,^{\circ}C$ and relative humidity of $50 \pm 5\%$ to simulate the operating room environment, which can ensure that the rabbit was comfortable and safe during friction experiments according to the describes in previous studies [40,41]. The tangential force, normal force and displacement were measured and recorded by using the UMT-II tribometer. The data files were analyzed in the Origin software (Version 8, OriginLab).

2.3. Mucosal surface characteristics

The wettability of small intestine mucosa is helpful to understand the friction trauma mechanisms of small intestine tissues under lubricated conditions. In this article, the wettability of small intestine mucosa was evaluated with the spreading parameter S, which could be expressed as [42]:

$$S = W_a - W_c \tag{1}$$

where the work of cohesion W_c was $W_c = 2\gamma_L$ according to the method in the literature [43], and the work of adhesion Wa was

$$W_a = \gamma_S + \gamma_L - \gamma_{SL} = \gamma_L(1 + \cos\theta) \tag{2}$$

According to the Young's equation described in the literature [44], γS, γL and γSL were the tensions of the solid/air, liquid/air and solid/liquid interfaces, respectively, and θ was the contact angle of the surface of the small intestine mucosa with the liquids [45].

The contact angle θ and the surface tension γ_L were tested with five replications by using a KRUSS contact angle measuring instrument (DSA30S, Germany). Fig. 2 shows the θ of the small intestine mucosa, which was performed as previously described and validated [46]. Additionally, the γ_L was measured according to the pendant drop technique [47].

After the tests, the rabbits were sacrificed by excessive amounts of anesthetic. Then the tested small intestine tissues were immediately