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Basic Study of Appropriate Knot-tying Force in the Gastrointestinal Tract for Development of Haptic Surgical Robot

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1.Introduction

While endoscopic surgery has frequently been performed as minimally invasive surgery in recent years, it is more difficult to perform than open surgery. Our experience with endoscopic surgery using the latest surgical robot daVinci at our hospital has shown that robotic surgery is beneficial in terms of the safe and easy performance of difficult surgical techniques, however, one of its drawbacks use of the robot does not impart a feeling that the surgeon's hands are touching the tissues, making meticulous procedures rather difficult (Anthony et al., 2004).

In ordinary open surgery or endoscopic surgery, surgeons apply knot-tying force spontaneously based on their experience and the feel of the tissues being handled. In robotic surgery, on the other hand, the force exerted is decided on the basis of visual information alone, such as the tautness of the thread and degree of deformation of the tissue. We therefore thought that objective data should be obtained to determine the optimal knot-tying force to apply when suturing during robotic surgery.

To achieve this goal we developed forceps for robotic surgery whose tips have six degrees of freedom (Matsuhira et al., 2003) and a new system at our hospital that displays information about force at the tip of the forceps measured by a sensor to the surgeons on monitor or via auditory signals. No studies have ever been conducted to investigate the relationship between knot-tying force and the efficiency of wound healing in the operated tissue, or to estimate the optimal knot-tying force for tissues. We thought that knowing the optimal knot-tying force for tissues in terms of the efficiency of wound healing would make it possible to tie knots based on the information concerning the force at the tip of the forceps displayed during robotic surgery, and to provide basic data in vivo for the development of robotic forceps that impart a feeling that the surgeon's hands are touching the sutures and tissues. The purpose of this study was to estimate the optimal knot-tying force by investigating the relationship between the force applied assessed on the basis of the information displayed on the surgeon's monitor and the efficiency of wound healing in the gastrointestinal tract in canine models.

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Wound healing in the gastrointestinal tract may be closely related to angiogenesis (Frank et al., 1991), and various growth factors may be involved in the process of wound healing (Glenn et al., 1992). Some studies have indicated that basic-fibroblast growth factor (bFGF) may be involved in the repair of epithelial cells, especially in the stomach and intestine (Dignass et al., 1992). In this study we examined angiogenesis and growth factor expression in the area of ligation as wound healing parameters to estimate the optimal knot-tying force for gastrointestinal tissues during suturing. We also attempted to determine the minimal knot-tying force that causes tissue ischemia by making real-time measurements of local blood flow (Oguma et al., 2007).

2. Methods

2.1 Canine models and suture and ligation methods

Twelve male Beagles were fasted for 24 hours before the start of the experiment. The animals were anesthetized by intravenous injection of sodium pentobarbital, and a laparotomy was performed through an upper abdominal midline incision. We cut by 1 cm length and then sutured by 1 cm length and full-thickness the stomach and jejunum by using different magnitudes of knot-tying force ranging from 0.5 N to 5.0 N (N: Newton). As a control ligation was performed without suturing under the same conditions and using the same knot-tying forces. The abdominal wound was closed, and on postoperative days (PODs) 4, 7, 11, and 14, a second laparotomy was performed to remove the stomach and jejunum. The specimens were stained immunohistochemically (anti-bFGF antibody) and with hematoxylin and eosin.

2.2 Local blood flow in the area of ligation

The knot-tying force that caused ischemia was determined by measuring local blood flow in the area of ligation. The wall of the stomach and jejunum was sutured and ligated using a series of knot-tying forces that ranged from 0.5 N to 5.0 N. Local blood flow at the site of first ligation was measured by laser Doppler velocimetry.

3. Results

3.1 Relation between the knot-tying force and local blood flow

There was an inverse correlation between knot-tying forces of 1.5 N and under and local blood flow. At forces of 2.0 N and over, local blood flow was slow and constant. (Fig. 1)

3.2 Relation between knot-tying force and microvessel density

On POD 7 in the stomach (Fig. 2), and on PODs 7 and 11 in the jejunum (Fig. 3), microvessel density in the submucosa at the sites that had been cut and sutured was highest at the knot-tying force of 1.5 N whereas there were no significant differences in microvessel density at any force used at the sites of ligation alone on any of the PODs. Nor were there any significant differences in microvessel density in the mucosa at the sites of cutting and ligation at any force used on any of the PODs. Microvessel density in the submucosa was low on the day of the operation. There were no significant differences in microvessel density in the mucosa or submucosa at the sites of ligation alone at any force used on any of the PODs.

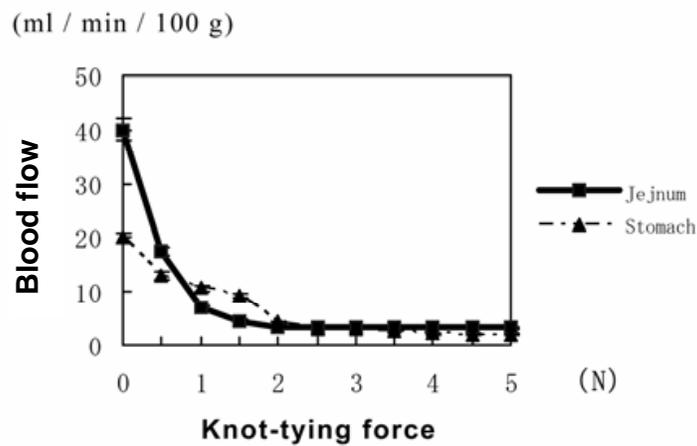


Figure 1. Relation between knot-tying force and local blood flow in the stomach and jejunum

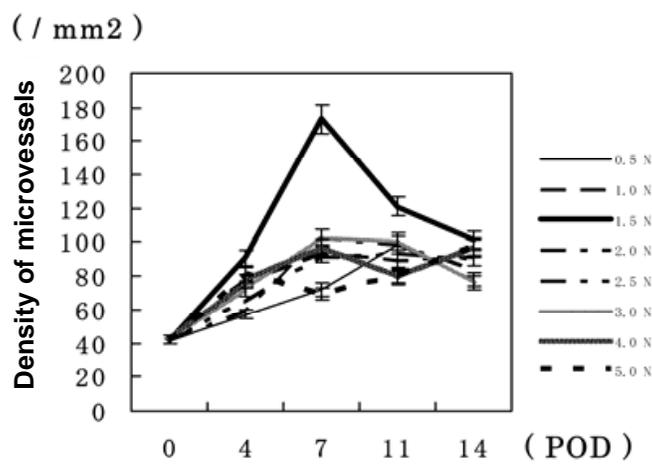


Figure 2. Relation between knot-tying force and microvessel density in the submucosa of the stomach

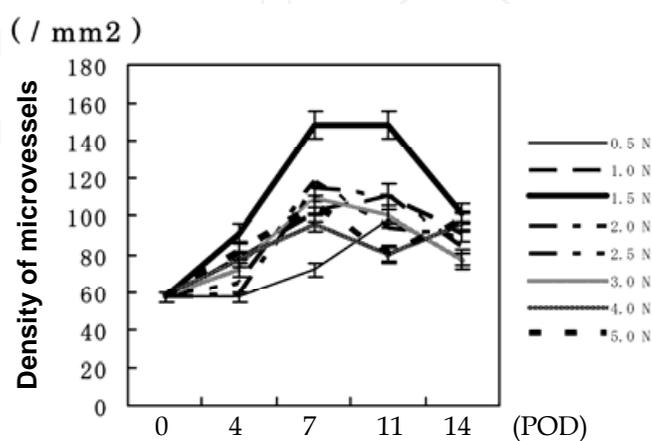


Figure 3. Relation between knot-tying force and microvessel density in the submucosa of the jejunum

3.3 Relation between knot-tying force and expression of bFGF

On PODs 4 and 7 in the stomach and on POD 11 in the jejunum, the density of bFGF-positive cells in the mucosa at the sites of cutting and ligation was highest at the knot-tying force of 1.5 N. There were no significant differences in the density of the bFGF-positive cells in the submucosa at any force used on any of the PODs (Fig. 4, 5).

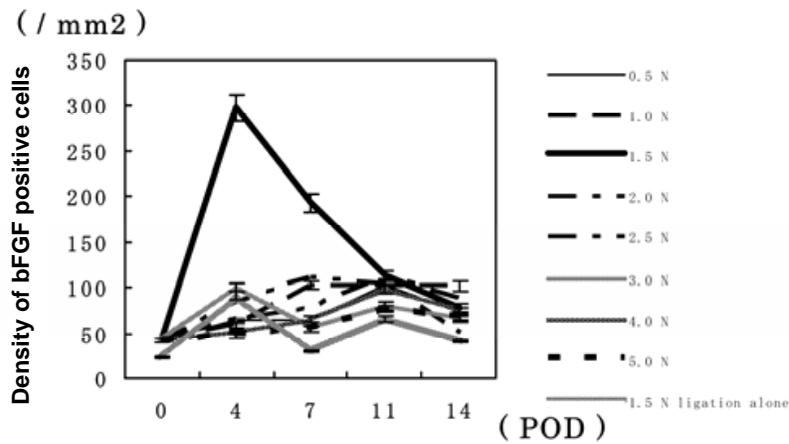


Figure 4. Relation between the knot-tying force and density of the bFGF positive cells in the mucosa of the stomach

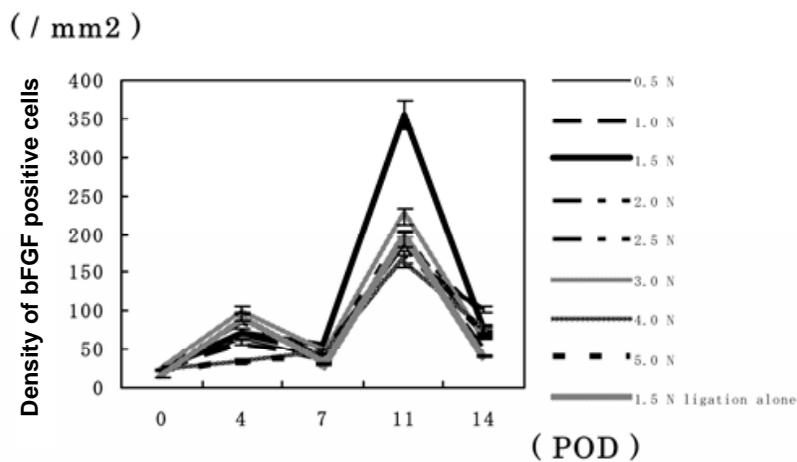


Figure 5. Relation between knot-tying force and density of the bFGF positive cells in the mucosa of the jejunum

4. Discussion

Assessment of the efficiency of wound healing in terms of the extent of angiogenesis and expression of growth factor at the wound sites in this study revealed that a knot-tying force of 1.5 N may be the most appropriate for optimal wound healing in the gastrointestinal tract of the Beagle model.

Wound healing can be evaluated on the basis of physical parameters and histological parameters. The physical parameters include shear stress and tensile strength, and some reports have suggested relationships between these parameters and wound healing (Thijs et al., 1990). Angiogenesis is one of the most important parameters for measuring wound healing, including the healing of wounds in the gastrointestinal tract (Seifert et al., 1997),

where it has been suggested that the angiogenesis that occurs during the wound healing process is mainly in the submucosa (Peter et al., 1989). Since application of tension or pressure at the repair site following anastomosis of the gastrointestinal tract is rare in actual clinical practice, we decided that a good histological parameter was more suitable to accurately evaluate wound healing in this situation. In this study we mainly evaluated angiogenesis as the most suitable parameter for assessing wound healing. No previous studies have investigated the relationship between the force applied when placing the sutures and the efficiency of wound healing in the tissue that was sutured, or estimated the optimal force to use when placing sutures in gastrointestinal tissues. In this study we estimated the most appropriate force to use when placing sutures to obtain optimal wound healing in the gastrointestinal tract by assessing the efficiency of wound healing in terms of the extent of angiogenesis as a histological parameter, and we adopted tissue microvessel density as one of the parameters to measure angiogenesis in this study.

Because microvessel density at the sites of ligation alone was lower than that at the sites of cutting and ligation the increase in microvessel density in the submucosa of the stomach and jejunum at the sites of cutting and ligation at the knot-tying force of 1.5 N appeared to be attributable to angiogenesis associated with wound healing and not to inflammation secondary to local tissue damage. Therefore, based on microvessel density in the submucosa we were able to objectively estimate that 1.5 N was the optimal knot-tying force for wound healing in the gastrointestinal tract of the Beagles.

We thought that wound healing would not occur at knot-tying forces less than 1.5 N, because agglutination of the edges at the sites of cutting and ligation was incomplete and the angiogenesis and fibrosis associated with the wound healing process were prevented. While some reports have suggested that local blood flow is important for wound healing (Chung et al., 1987), no previous studies have investigated the relationship between knot-tying force and local blood flow. The results of this study suggest that knot-tying forces greater than 1.5 N would make the tissue ischemic and prevent efficient wound healing.

To select the range of knot-tying forces to test in our study, three surgeons were blindfolded and asked to place several sutures manually, and we measured the knot-tying force used in each instance. The forces applied during tying ranged from 0.8 N to 2.0 N, although there were a few differences among the three surgeons. We therefore selected 0.5 N to 5.0 N as the range of knot-tying forces to test in our study.

It has been reported that bFGF may be related to acceleration of angiogenesis, formation of granulation tissue, and proliferation of fibroblasts (Spyrou et al., 2002). In this study we measured the expression of bFGF at the sites of cutting and ligation as a diachronic study and investigated the relationship between knot-tying force and expression of bFGF. The increase in expression of bFGF in the mucosa of the jejunum at the sites of cutting and ligation was observed later than the increase in microvessel density in the submucosa. In the stomach, the expression of bFGF in the mucosa preceded the increase in microvessel density in the submucosa. It has been reported that bFGF is the major contributor to the formation of granulation tissue and increase in number of fibroblasts in the intestine during the process of wound healing, and that angiogenesis is also induced mainly by bFGF. The timing of the expression of bFGF in the stomach differed from the timing of the expression in the jejunum, and the role of bFGF in wound healing would seem to differ in different organs.

In recent years the development and application of robotic surgery has progressed to such an extent that the poor flexibility of the tips of forceps, which was one of the drawbacks of

endoscopic surgery, has been overcome, making telesurgery possible, and suturing and ligation can now be performed more smoothly (Cadiere et al., 2001). On the other hand, since a sense of touching the tissue is not imparted to the surgeon's hands from the tip of the forceps, use of appropriate force during ligation has been difficult. We developed a system that displays information concerning the force at the tip of the forceps to the surgeon on a monitor or via auditory signals, and based on the results of this study the system appeared makes it possible to apply appropriate force during suturing and ligation in the gastrointestinal tract. We are now planning to develop a system in which the force at the tip of the forceps that directly imparts a sense of touch to the surgeon's hands. We need to program information on variable senses of touch to this system to create a database. We believe that the results of our study will serve as useful data for surgery on live beings and contribute to the development of robotic forceps with a sensor of touch in the future.

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The first generation of surgical robots are already being installed in a number of operating rooms around the world. Robotics is being introduced to medicine because it allows for unprecedented control and precision of surgical instruments in minimally invasive procedures. So far, robots have been used to position an endoscope, perform gallbladder surgery and correct gastroesophageal reflux and heartburn. The ultimate goal of the robotic surgery field is to design a robot that can be used to perform closed-chest, beating-heart surgery. The use of robotics in surgery will expand over the next decades without any doubt. Minimally Invasive Surgery (MIS) is a revolutionary approach in surgery. In MIS, the operation is performed with instruments and viewing equipment inserted into the body through small incisions created by the surgeon, in contrast to open surgery with large incisions. This minimizes surgical trauma and damage to healthy tissue, resulting in shorter patient recovery time. The aim of this book is to provide an overview of the state-of-art, to present new ideas, original results and practical experiences in this expanding area. Nevertheless, many chapters in the book concern advanced research on this growing area. The book provides critical analysis of clinical trials, assessment of the benefits and risks of the application of these technologies. This book is certainly a small sample of the research activity on Medical Robotics going on around the globe as you read it, but it surely covers a good deal of what has been done in the field recently, and as such it works as a valuable source for researchers interested in the involved subjects, whether they are currently “medical roboticists” or not.

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