マニピュレータ先端部は臨床での有用性を考慮し，全て分解・滅菌可能であり，かつ本体駆動部に取り付け具なしで取り付けられる機構になっている．

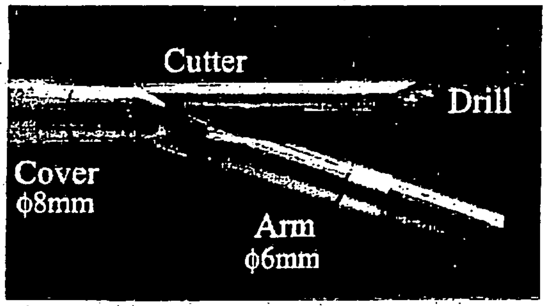


**Fig.3** Endeffector of the manipulator

3．評価実験

3．1 屈曲特性評価

前立腺屈曲のための先端部アームは，先端にかかる負荷によって特性が異なることが予備実験によりわかっている．従って，先端に負荷を加えた状態でのアームの屈曲特性を評価した．アーム先端に，50gfずつ荷重を加えていき，マニピュレータに 25° 屈曲する指令を送り，実際に屈曲する角度を測定した．屈曲特性の結果を Fig. 4 に示す．

アームの屈曲角度は，負荷を大きくするほど指令値に対し出力値が小さくなることがわかった．最大誤差は負荷が 300gf の時であり，その値は 6.3° であった．また屈曲のばらつきに関しては標準偏差の平均は 0.7° であった．

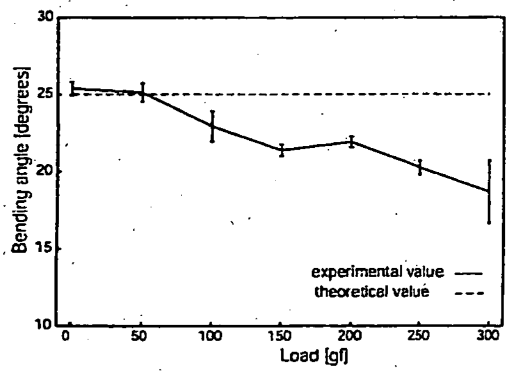


**Fig.4** Bending characteristics of the arm with loaded condition

3．2 ファントム実験

前立腺のファントムとしてゼラチンを用い，屈曲および切除実験を行った．前立腺尿道部 45mm，肥大前立腺外径 50mm の円柱型ゼラチンモデルに，尿道にあたる直径 4mm の空洞をつくり，これにマニピュレータ先端部を挿入し，屈曲・切除を行った．ファントム実験の屈曲・切除の様子を Fig.5 に，切除したモデルの断面形状を Fig.6 に示す．

切除の手順は以下の通りである．マニピュレータを経尿道的に挿入し，始めにアームを 45° 屈曲させ，カッターを 40mm 挿入し切除吸引を行った．その後アームの角度を 5° 戻す度にカッターを挿入し，切除吸引を行った．

評価項目は，1 平面内の切除における切除範囲と，挿入口の損傷の大きさを測定した．

1 平面切除における平均切除面積は 65.3mm$^2$ であり，カッター挿入部の大きさの平均は直径 3.8mm であった．


**Fig.5** Resection procedure: (a) Cutter insertion at bending angle 30° (b) Cutter insertion at bending angle 15°

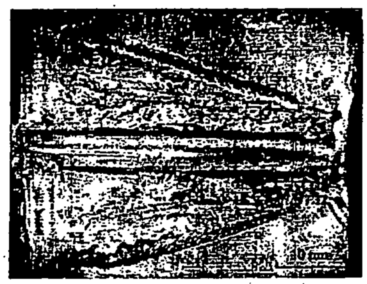

**Fig.6** Cross section of gelatin model after resection

4．考察

負荷を与えたアームの屈曲特性は，負荷の大きさに伴い屈曲角度が小さくなった．屈曲機構で用いるリンクの変形が最も大きく影響を与えていると考えられる．しかしどの負荷においても 1° 以下の再現性が得られているため，荷重・実測値をもとに屈曲角度の補正をすることが可能である．

ファントム実験においては，アームが組織を確実に変位させることができること，3.8mm の小孔から非常に広い範囲の組織を切除・吸引できることがわかった．今後はより肥大前立腺組織に近いファントムを用い，本機構の有用性を評価していく．

5．まとめ

本研究では経尿道的前立腺切除術のための管状組織低侵襲切除マニピュレータを開発した．屈曲切除機構と灌流切除機構により低侵襲な切除と，短時間での切除を実現した．

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3. Q. Mei, *et al*, PROBOT – A Computer Integrated Prostatectomy System, Visualization in Biomedical Computing, 1311, pp581-590, 1996
4. K. Matsumiya, *et al*, A New Robotic Device for Less Invasive Transurethral Resection of the Prostate, Computer Assisted Radiology and Surgery, pp134-138, 2000

# SP2-I: Medical Robotics II

## Room I, 16:10-17:30, Saturday, October 2, 2004

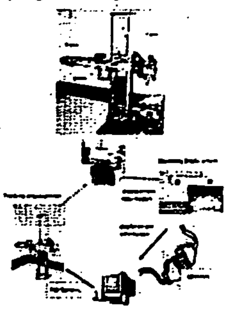


### SP2-I1 16:10-16:30

#### Development of SPINEBOT for Spine Surgery

G.B. Chung, S.G. Lee, S.M. Oh, B.-J. Yi, W. K. Kim, Y.S. Kim, J.J. Park, and S.H. Oh
Center for Intelligent Surgery System, Hanyang University, KOREA

- The surgical procedure for spinal operation and possible roles of the robot are discussed.
- The expected simplest role of SPINEBOT is to provide the guide to locate and orient the surgical tools more accurately.
- The tracking experiment to compensate for the respiratory movement of the human body is conducted by using optical tracking system.
- The interaction force between the end-effector of SPINEBOT and the mockup vertebra is measured to verify the applicability of SPINEBOT to tasks of boring and inserting screws automatically.



### SP2-I2 16:30-16:50

#### A new mechanical birth simulator : BirthSIM

R. Silveira, O. Dupuis, M.T. Pham, T. Redarce, M. Bétemps
Institut National des Sciences Appliquées de Lyon - France
Hôpital de la Croix Rousse Lyon - France

BirthSIM is a complete system for training and testing new techniques in obstetric practice. It is composed of three parts:

•a physical new-born head and a maternal pelvis manikin,

•an interface pressure system,

•a pneumatic actuator that develops an active resistance.

BirthSIM

Driven by a computer, BirthSIM can simulate the contractions and mimic birth complications.

### SP2-I3 16:50-17:10

#### A Tubular Organ Resection Manipulator for Transurethral Resection of the Prostate

Ryuji Hashimoto Dayoung Kim Nobuhiko Hata Takeyoshi Dohi
Graduate School of Information Science and Technology
The University of Tokyo, JAPAN

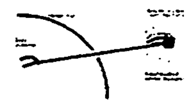
- The manipulator realizes less invasive resection of the prostate for TUR-P surgery
- Two novel mechanisms:
  - Prostate displacement mechanism
  - Perfusion-resection mechanism
- Description of manipulator design
- Accuracy evaluation & Phantom study

### SP2-I4 17:10-17:30

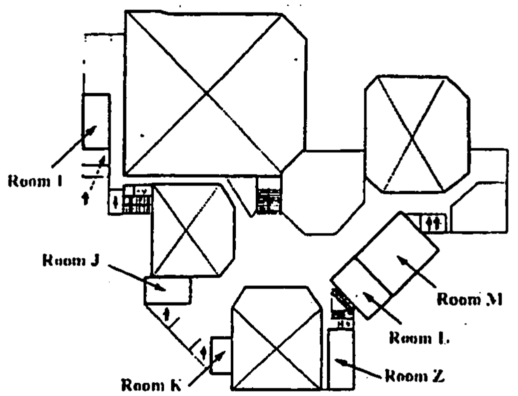
#### Palpation Instrument for Augmented Minimally Invasive Surgery

Maria Vatshaug Ottermo, Øyvind Stavdahl and Tor A. Johansen
Norwegian University of Science and Technology, Norway

- A preliminary design of a remote palpation instrument for Minimally Invasive Surgery with tactile feedback
- A piezoelectric sensor array attached to the instrument's end effector will provide tactile information
- The sensor array is 24*8 $mm^2$ and consists of 30 sensors
- The tactile information will be sent to surgeon's fingers via a tactile display
- The tactile display is 32*18*45 $mm^3$ and consists of 30 micro motors



A sketch of the instrument with tactile sensor and display




Third Floor, Room I

Proceedings of 2004 IEEE/RSJ International Conference on
Intelligent Robots and Systems
September 28 - October 2, 2004, Sendai, Japan

# A Tubular Organ Resection Manipulator for Transurethral Resection of the Prostate

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***Abstract*— Transurethral resection of the prostate (TUR-P) is a common treatment for Benign Prostatic Hyperplasia (BPH). However, the damage to the mucous membrane of the urethra leads to the complications. This paper reports a tubular organ resection manipulator for transurethral resection of the prostate which can minimize damage to the mucous membrane of the urethra using a prostate displacement mechanism and a continuous perfusion-resection mechanism. The manipulator has an arm, a cutter and a drill at the endeffector, and has 4 degrees-of-freedom: bending the arm, translating the cutter, rotating the drill and rotating the endeffector. The arm displaces the prostate, and the cutter is inserted linearly into the prostate and removes enlarged tissue by drilling. Combination of the arm and cutter enables the manipulator to remove sufficient volume of enlarged prostate through small incision on the urethra, thus minimizing the damage to the urethra. After finishing one plane cutting, the manipulator rotates its body and removes another part of the prostate gland. In performance experiments, each mechanism (bending motion, insertion, and body rotation) had high repeatability within 1.0 degree and within 0.1 mm. In phantom study, the manipulator could displace gelatin model accurately with sufficient power, and could reach and remove wide range of sample tissue (589.2 mm$^2$ in one procedure). These results showed that the manipulator can displace the prostate and remove sufficient volume of the prostate tissue through small incision on the urethra.**

## I. INTRODUCTION

Benign prostatic hyperplasia (BPH) is a noncancerous enlargement of the prostate gland. As a man ages, the prostate becomes enlarged and places pressure on the urethra. This leads to urination trouble and dysfunction of the bladder and kidney. More than half of all men in their 60s, and as many as 80 percent of men in their 70s and 80s, have some symptoms of BPH [1], [2].

Transurethral resection of the prostate (TUR-P) is currently standard method of cure for BPH. As compared with the conventional open surgery, TUR-P has advantages such as less invasive and shorter hospitalization. In the TUR-P procedure, the surgeon inserts a resectoscope through the urethra, and cuts the prostate tissue into small pieces with an electrical loop during the 90-minute operation. The resected tissue are carried by the perfusate into the bladder and then flushed out at the end of the operation. After surgery, the removed tissue is routinely checked for hidden cancer cells [3], [4].

However, some complications are possible with TUR-P procedure. Urinary tract infection (UTI) occurs with damage to the mucous membrane of the urethra during tissue resection of an enlarged prostate. TUR syndrome, which leads to dizziness and nausea, occurs with absorption of perfusate in extended surgery. TUR-P procedure by nature is difficult procedure for physicians due to limited view of surgical field in resectoscope (Fig. 1). This leads to the perforation of the prostate capsule, resulting in rectal injury or bladder damage [5], [6], [7].

Some devices have been proposed by several groups to avoid the TUR-P complications. Davies developed a PROBOT for TUR-P surgery under accurate control, with guidance provided by a 3D model of the prostate generated from the ultrasound images [8], [9]. Accurate and repeatable cutting by the manipulator realizes safe cutting of the prostate, and prevents bleeding and damage to sphincter muscle and nerves. Matsumiya has proposed a preliminary design for a prostatectomy cutter which reaches the prostate via a small incision on the urethra [10]. These devices have possibility of reducing some complications. However, no device has focused on above two complications; UTI and TUR syndrome which is the serious problems in TUR-P procedure, and no device has reported that can both minimize the damage to the urethra, and remove enlarged prostate in short time.

As a solution for these problems, we reported a transurethral prostate resection manipulator which can prevent the damage to the urethra and remove sufficient volume of the prostate in short time [11]. In previous study, the prototype had three degrees-of-freedom and could not complete whole range resection. Furthermore we had to develop the whole system such as a controller for surgeon, and image guidance for safe resection. The objectives of the current study are to complete the further degree-of-freedom of the manipulator, and to confirm feasibility of proposed prostatectomy. This paper reports 1) description of the newly developed tubular organ resection manipulator, 2) its mechanical performance analysis and 3) results of phantom experiment using a gelatin model to evaluate usefulness of less invasive resection mechanism.

## II. PROSTATE DISPLACEMENT MECHANISM

### *A. System Requirement*

In order to overcome the complications of TUR-P procedure, detailed requirements for the manipulator system is summarized as follows:

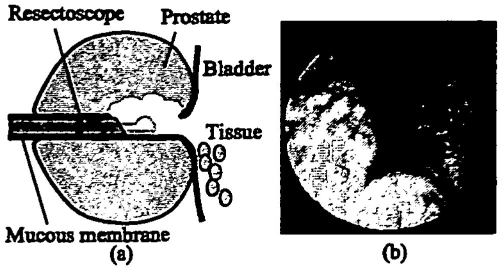


Fig. 1. Conventional resection procedure of TUR-P. The problems of TUR-P procedure is 1) damage to the mucous membrane of the urethra (a), 2) absorption of perfusate in extended surgery and 3) deep cutting due to limited view in resectoscope (b).

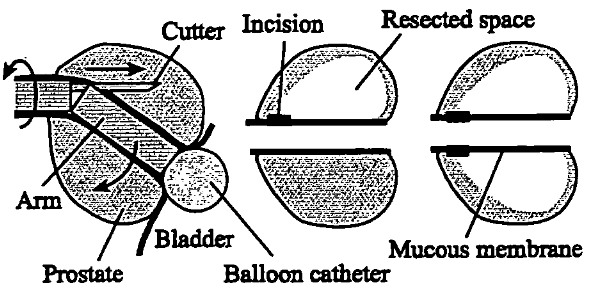


Fig. 2. Prostate displacement mechanism for minimizing damage to the mucous membrane. The end effector of the manipulator has the arm and cutter. Combination of the arm and cutter enable the manipulator to resect sufficient volume of the prostate tissue through small incision.

- The manipulator should remove the tissue through small incision on the urethra.
- The manipulator should remove sufficient volume of the tissue in short time.
- The system should provide enough image information which surgeon can grasp position between the end effector and the target tissue.
- The end effector of the manipulator should be small enough to be inserted through urethra, and be demountable and sterilizable.

Based on these system requirements, we proposed two novel mechanisms and resection system described below.

### *B. Prostate displacement mechanism*

Figure 2 shows the prostate displacement mechanism to prevent damage to the mucous membrane of the urethra. End effector of the manipulator has an arm and a cutter. Firstly, the manipulator is inserted through the urethra. Then the arm bends to displace the enlarged prostate, and the cutter is inserted into the prostate to remove prostate tissue by cutting.

While the cutter cuts the enlarged tissue moving only linearly, the arm can change its angle. Thus the possibility of incision in the mucous membrane can be restricted to a single point.

Organs such as the bladder and sphincter muscle are situated around the prostate, and should not be damaged. We thus attach a balloon catheter to the end of the arm.

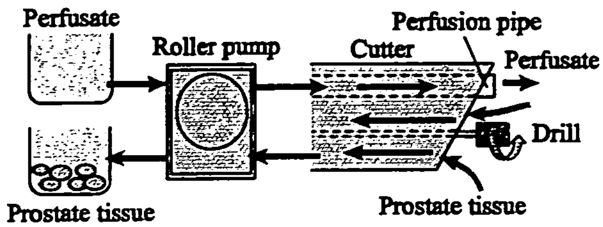


Fig. 3. Continuous perfusion-resection mechanism for rapid resection. Roller pump inlet the perfusate into the prostate through perfusion pipe, then the drill cut the prostate tissue, then the pump aspirate the prostate tissue and perfusate as fluid outside of the body.

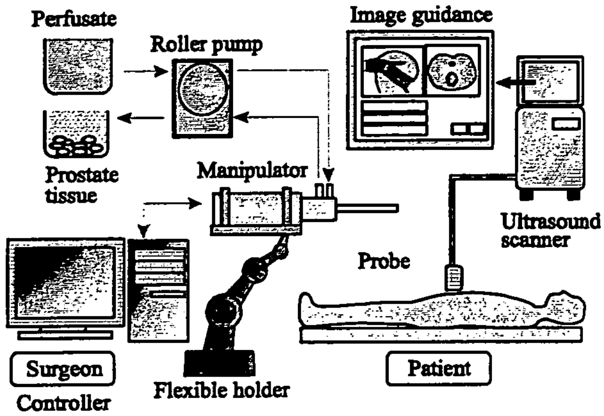


Fig. 4. Conceptual model of the complete system. The system consists of three parts; a manipulator, an image-guided system and controller. The surgeon controls the manipulator from the controller and resects the prostate tissue while watching the multi slice images from the image-guided system.

When the balloon is inflated, it holds the manipulator steady against the urethra, and keeps the position between the manipulator and the prostate, thus preventing damage to these organs.

### *C. Continuous perfusion-resection mechanism*

Figure 3 shows the continuous perfusion-resection mechanism for rapid resection. The cutter is equipped with a drill and a perfusion pipe. While the cutter is inserted into the prostate, the drill continues to cut the enlarged tissue into small piece by rotating. A roller pump inlet perfusate into the prostate through the perfusion pipe; the perfusate is mixed with the prostate tissue and is removed outside the body by the roller pump. Using this mechanism, the manipulator can cut and remove the enlarged tissue at the same time, thus realizing a short time resection.

## III. System Configuration

The system has three parts: a manipulator, an image-guided system, and a controller (Fig. 4). The manipulator is fixed to a flexible holder (Point Setter, Mitaka Kouki Inc., Japan). Firstly, the manipulator is inserted into the prostate through the urethra. The flexible holder is then locked, and the surgeon controls the manipulator using a controller under the ultrasound guidance. We use a transrectal or

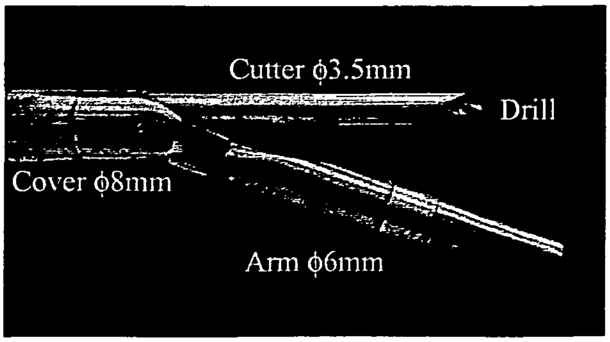


Fig. 5. End effector of the manipulator has the arm, cutter and drill. The end effector has 4 degree-of-freedom; 1) bending the arm, 2) translating the cutter, 3) rotating the drill and 4) rotating the end effector.

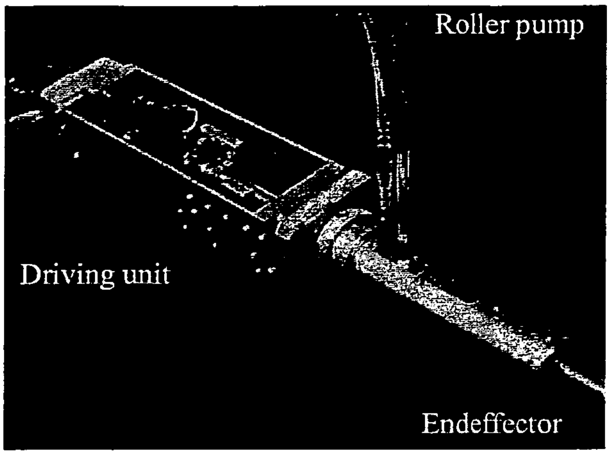


Fig. 6. Driving unit of the manipulator. Driving unit has four motors, three photo sensors and two ball screws, and delivers generation power to the end effector. Connection mechanism realizes quick connection between the driving unit and the end effector.

transabdominal ultrasound probe (EUP-C514 EUP-CC531, Hitachi Medical Co., Japan) for image guiding. Ultrasound device (EUB-525, Hitachi Medical Co., Japan) provides the multi slice imaging of the prostate. Using US guidance, the surgeon can easily grasp the position between the end effector and prostate and the other organs. Thus the possibility of unexpected damage to the prostate capsule or the bladder neck can be reduced. These devices realize a minimally invasive, efficient and safe resection.

### A. Manipulator Specification

We developed the tubular organ resection manipulator. The manipulator consists of an end effector and a driving unit.

*1) 4 Degrees-of-freedom end effector:* Figure 5 shows the end effector which has 4 degree-of-freedom: 1) bending of the arm, 2) translating of the cutter, 3) rotating the drill and 4) rotating the end effector. The arm is 6 mm in diameter and 40-mm in length. The arm can change its angle range of 0 to 45 degrees, with a resolution of 0.1 degrees. Length of the arm can be changed 20 to 50 mm because length of intraprostatic urethra varies by patients.

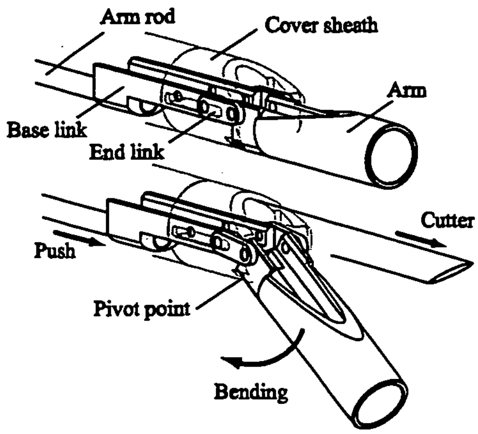


Fig. 7. Slider linkage mechanism consists of cover sheath, arm rod, base link, end link and arm. The actuator pushes the arm rod, and then base link transmit its power to the end link, then the end link bends the arm around its pivot point.

The diameter of the cutter is 3.5 mm. Its stroke length is 40 mm, with a resolution of 0.1 mm. The diameter of the cover sheath, which is inserted in the urethra, is 8 mm. This is the same size as the resectoscope. The manipulator can rotate its end effector range of -180 to 180 degrees. These elements are demountable and sterilizable. Using these 4 degrees-of-freedom, the end effector can remove sufficient volume of prostate tissue through small incision on the urethra.

The driving unit consists of motors, photo-sensors and ball screws. The rotational velocity and direction of the motor is controlled from a console. The ball screws transform rotation of the motors into translation. The photo-sensors are used to tune the zero-point of the arm and cutter. These elements are unsterilizable, so the driving unit has to be covered by a drape during the operation. The size of the driving unit is 50×65×235 mm.

*2) Displacement and Perfusion-resection mechanism:* In order to displace the enlarged prostate accurately, we adopted a slider linkage mechanism for bending (Fig. 7), because it realizes greater stiffness and fewer backlashes than a wire-driven system. When the actuator pushes or pulls a base link, the end link bends or extends the arm around its pivot point. Figure 8 shows a working space of the arm. Combination of arm bending and body rotation, the arm can reach whole range of the enlarged prostate model.

Figure 9 shows the detail of the continuous perfusion-resection mechanism. The mechanism consists of perfusion pipe (0.5 mm in outer diameter) and drill (2.4 mm in diameter). The roller pump inlet the perfusate into the prostate through the perfusion pipe, then drill cuts the prostate tissue into small pieces, and the pump aspirates the tissue and perfusate through another port of the cutter. Output pressure of the roller pump is 200 kPa and maximum flow rate of the perfusate is 90 $ml/min$. This mechanism realizes a short time resection.

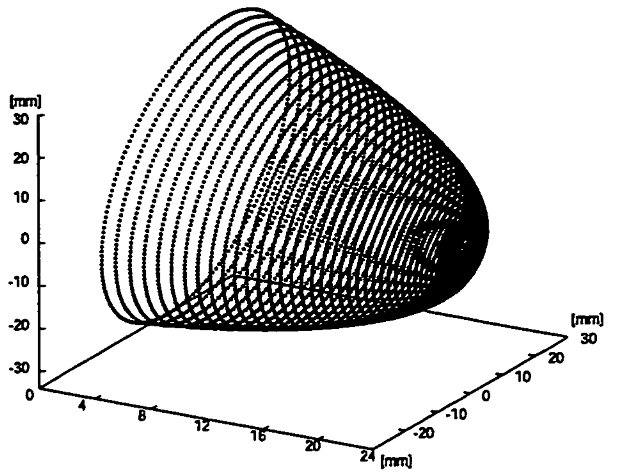


Fig. 8. Working space of the arm. The end of the arm can reach whole range of the enlarged prostate using bending of the arm and rotation of the body.

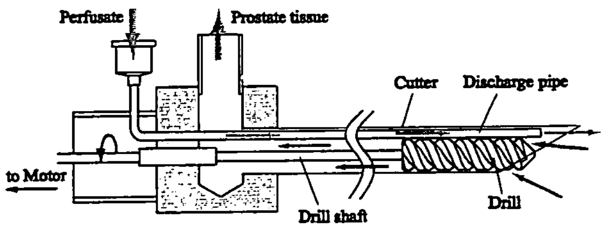


Fig. 9. Detail of the continuous perfusion-resection mechanism. The cutter has the discharge pipe and drill. The pump inlets the perfusate through the discharge pipe, and the motor rotates drill shaft and transmits the power to the drill. The pump aspirates the prostate tissue through another port of the cutter.

3) *Connection mechanism for sterilization:* The manipulator has a connection mechanism which provides fixture-free connection of the sterilizable end effector and the unsterilizable driving unit. We equipped the connector with a coupling for drill rotation, and springs for translation of the arm and cutter translation. The arm bends in response to the driving unit pushing the arm link. The arm extends when the spring pulls the arm link. The cutter is moved by the same mechanism as the arm. This mechanism realizes clear separation between sterilizable area and unsterilizable area.

4) *Computer-based master-slave controller system:* We adopted master-slave controller system for accurate and safe operation. Surgeon controls the 3 degrees-of-freedom controller corresponding to 3 degrees-of-freedom of the manipulator; bending arm, inserting cutter and rotating body. The controller has three potentiometers for each degree-of-freedom motion. Control PC detects surgeon's input from the controller, and then PC outputs the command to the manipulator and controls actuation. A/D board manages input from potentiometers of master controller. D/A board manages output to control speed of actuators. Digital I/O board manages input from photo sensors of the manipulator and decision of actuators' rotation direction.

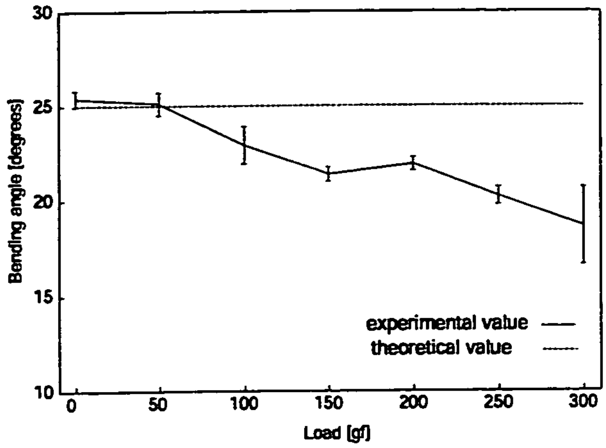


Fig. 10. Bending characteristics of the arm with various loaded condition. Bending angle tended to become small as heavy load.

## IV. Evaluation Study and Results

### A. *Performance experiments*

1) *Accuracy and repeatability with unloaded:* The accuracy and repeatability of arm bending, cutter insertion and body rotation were evaluated. Each motion was evaluated in unloaded condition. The displacement of cutter insertion was measured with CCD laser displacement sensor (LK-2000, KEYENCE, Japan). The rotation of arm bending and body rotation were measured with high resolution digital microscope (VH-8000, KEYENCE, Japan). Table I shows working range, maximum error and standard deviation of each motion.

TABLE I

ACCURACY AND REPEATABILITY EVALUATION

| | | |
|---|---|---|
| Arm (unloaded) | Working range [degrees] | 0 to 48.5 |
| | Maximum error [degrees] | 1.2 |
| | Repeatability [degrees] | ±0.5 |
| Cutter (unloaded) | Working range [mm] | 0 to 42.1 |
| | Maximum error [mm] | 0.4 |
| | Repeatability [mm] | ±0.2 |
| Body (unloaded) | Working range [degrees] | ±180 |
| | Maximum error [degrees] | 1.4 |
| | Repeatability [degrees] | ±0.7 |

The working range of each degree-of-freedom covered wider range than required range that we decided first as requirement specification. Repeatability of each motion was less than 1.0 degree or less than 1.0 mm.

2) *Bending characteristics with loaded condition:* Bending characteristics of the arm was evaluated. In previous study, bending characteristics of the arm changes according to the load at the arm [11]. We added every 50 gf load to the end of the arm. PC input command to bend the arm with 25 degrees. Then we compared actual bending angle to theoretical 25 degrees. The result was shown in Fig. 10.

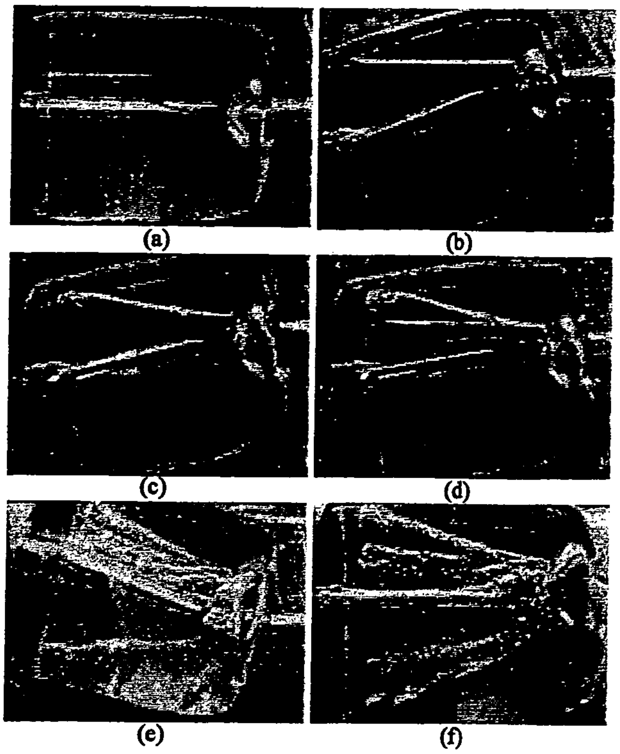


Fig. 11. Resection procedure of the end effector. a) Firstly, the end effector is inserted through the urethra. b) The arm displace the tissue and the cutter is inserted into the tissue. c) At the same time, the cutter aspirates the tissue outside of the body. d) The arm changes its angle and continues resection. e) The end effector rotate its body, and starts resection at opposite side of the tissue. f) The manipulator finishes one plane resection, and continues resection in another plane of tissue.

Bending angle of the arm became smaller as large load. Maximum error of bending angle was 6.3 degree at 300 gf load. Average standard deviation was 0.7 degree.

### *B. Phantom experiments*

Resection performance was evaluated using phantom of gelatin model. Size of the gelatin model was 45 mm in height, 50 mm in diameter, shaped cylinder which was same size of the enlarged prostate. There was tubular space at center of cylinder as urethra model which was 45 mm in length, 4 mm in diameter. Resection procedure was shown in Fig. 11. Firstly the manipulator was inserted through urethra. The manipulator bended its arm to displace the tissue, and cutter was inserted into the tissue. At the same time the cutter aspirated resected tissue outside of the body. The arm changed its angle and continued resection.

In this experiment, first the manipulator bended the arm in 45 degrees and started resection, inserting the cutter 40 mm. Then the manipulator bended back the arm every 5 degrees and started resection. We measured resected space of gelatin model in one plane, and measured size of insertion point which was incision on the urethra. The results were 589.2 $mm^2$ of resection space and 3.8 mm in diameter of insertion point.

Figure 12 shows the cross section of the gelatin model.

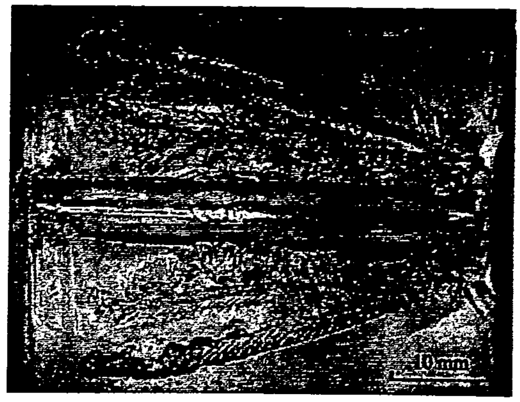


Fig. 12. Cross section of the gelatin model. The urethra model was remained and only insertion point of the urethra model was damaged. The end effector could remove wide range of gelatin model through small incision on the urethra model.

The urethra model was not damaged at all except only insertion point. The manipulator could remove sufficient, wide range of gelatin model through small incision on the urethra.

## V. Discussion

We have developed a tubular organ resection manipulator for transurethral resection of the prostate that realizes minimal damage to the urethra and short time resection.

We confirmed that the manipulator had high repeatability of less than 1.0 degree in bending motion and body rotation, less than 0.5 mm in cutter insertion under unloaded condition. These results showed that the manipulator could be accurately controlled by the surgeon.

In the performance experiments of bending characteristics with loaded condition, we confirmed that the end effector had sufficient power to displace the enlarged prostate with high repeatability of 0.7 degrees on the average. Bending angle tended to be small with as heavy load, and maximum error was 6.3 degrees at loaded with 300 gf. Main cause of the error was deflection of linkage mechanism. Because of high repeatability of bending motion, we can cancel these errors and control accurate bending by calibration from experimental value.

The phantom experiments confirmed that the manipulator could remove wide range of tissue from phantom gelatin model through small incision on the urethra. Damage on the urethra was limited only 3.8 mm, and the resection range in one plane was 589.2 $mm^2$. These results show that the manipulator covered 66.5 percent area of gelatin model (whole area of cross section of gelatin model was 884.8 $mm^2$ on the average). It was enough to reduce the pressure on the urethra because transition zone of the prostate which should be mainly removed is located near the neck of the bladder, and the manipulator can reach and remove whole area of tissue around the neck of bladder.

In another respect, the manipulator has a potential as a biopsy tool for prostate cancer; that is, as the tool that removes tissue for examination. Detection of early prostate cancer is an important function because BPH and prostate cancer are strongly related, and cancer cells are found in 10 percent of resected samples after surgery [3].

We are going to develop master-slave controller which the surgeon manipulates and to complete master-slave system. Force feedback of arm bending motion is needed for safe and accurate resection. We are thus going to equip a strain sensor for detecting load at the end of the arm. Other future work will include the development of an image-guided system in which we use transrectal or transabdominal ultrasonography to identify the locations of the end effector and prostate.

In conclusion, we have developed a tubular organ resection manipulator for transurethral resection of the prostate. We have evaluated the accuracy performance of 4 degrees-of-freedom motions and resection performance using gelatin model. We have confirmed that the each motion was highly accurate and had high repeatability and that the manipulator could remove wide range of gelatin model through small incision on the urethra. We are sure that our manipulator is capable of accurately displacing an enlarged prostate and removing sufficient prostate tissue with less damage to mucous membrane of the urethra.

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04(V)-35

# 経尿道的前立腺切除マニピュレータによる低侵襲切除システム

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# Minimally Invasive Resection System using Transurethral Prostate Resection Manipulator

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**Abstract:** Transurethral resection of the prostate (TUR-P) is a common treatment for Benign Prostatic Hyperplasia (BPH). However, the damage to the mucous membrane of the urethra and narrow field of view from resectoscope leads to the serious complications. This paper reports minimally invasive resection system using a transurethral prostate resection manipulator. The system consists of three parts: the manipulator, ultrasound image-guided system, and master-slave controller for surgeon. The manipulator can remove sufficient volume of enlarged prostate through small incision on the urethra by using prostate displacement mechanism, thus minimizing the damage to the mucous membrane of the urethra. The surgeon manipulates master controller under multi-slice ultrasound images provided by transrectal ultrasonography. In performance experiments, slave manipulator had high repeatability of resection motion: less than 1mm or 1deg. of each degree-of-freedom. In phantom study, the manipulator could displace gelatin model accurately, and could remove sufficient volume of the tissue through 3.7mm incision on the urethra model. These results showed that the manipulator can displace the prostate accurately and remove sufficient volume of the prostate tissue through small incision on the urethra.

**Key words:** Transurethral resection of the prostate, Benign prostatic hyperplasia, Minimally invasive robotic surgery

## 1. はじめに

経尿道的前立腺切除術は，前立腺肥大症の手術方法として広く一般的に用いられている．しかし，尿道粘膜の損傷による尿路感染症・排尿時刺激症が問題視されている．また，切除鏡の限られた画像・情報量をもとに切除を行うため，周辺組織や目的部位深部を傷つけるなどの穿孔と呼ばれる合併症を起こす可能性も非常に高い[1]．したがって，尿道粘膜の損傷を抑えた低侵襲な切除を行い，かつ安全な誘導のもと正確に切除を行うデバイスおよびシステムの開発が必要とされる．

我々はこれまでに，経尿道的前立腺切除術のための低侵襲切除方法を考案し，尿道粘膜の損傷を抑え切除を行える管状組織低侵襲切除マニピュレータの開発を行ってきた[2]．本研究では，本マニピュレータを用いた低侵襲切除システムの詳細，新たな機構・自由度を付加したマニピュレータの詳細，そして臨床への有用性の評価についての報告を行う．

## 2. 低侵襲切除システム

Fig.1 に低侵襲切除システムの全体像を示す．システムは，マニピュレータ・超音波画像誘導システム・術者操縦用マスタコントローラの三部から構成されている．以下それぞれの機能・詳細について述べる．

### 2.1. マニピュレータ

マニピュレータ先端部にはアーム・カッター・ドリルが装備されている．アームの屈曲により前立腺を変位し，カッターを直線的に前立腺組織に挿入し，ドリルにより小片に切除し，体外に取り除く．アーム屈曲角度とカッターの挿入位置を変化させて，1 点の損傷部を通じて，多くの肥大組織を低侵襲的に切除することができる．
また 1 平面内の切除が終了した後，マニピュレータ先端部を先端軸に沿って回転することにより，他の平面においても同様の低侵襲切除が行える．アーム屈曲 45deg. カッター挿入 40mm，ドリル回転，ボディ回転 360deg.の 4 自由度により肥大前立腺の低侵襲切除を実現する．

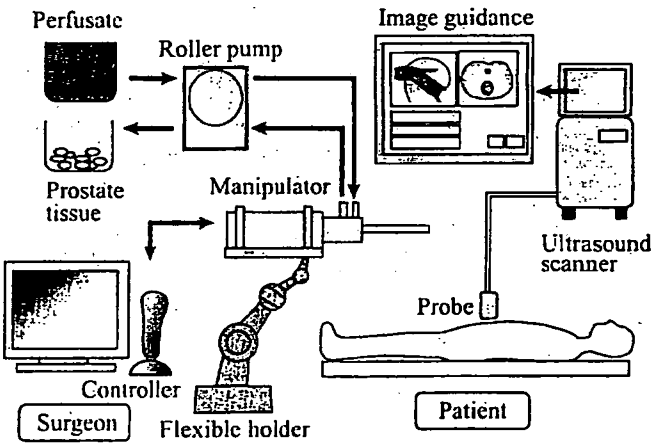


**Fig. 1.** Minimally invasive resection system. The system consists of three parts: the manipulator, image-guided system and master-slave controller.

### 2.2. 超音波画像誘導

従来 TUR-P 手術法では，切除鏡からの一面的な画像情報のもと切除を行っており，術具・患部の位置関係の把握が困難であった．本システムでは超音波断層像による複数断面画像誘導を想定している．これにより，マニピュレータ・患部および周囲組織の位置関係の把握が用意であり，安全かつ術者に負担の少ない切除法を実現できる．

### 2.3. マスタ・スレーブ方式の操縦

術者は画像誘導下でマスタコントローラを操縦し低侵襲切除を行う．スレーブマニピュレータはポイントセッタのような保持具に固定され切除を行う．マスタスレーブ方式の採用により，術者の手振れ等の誤動作を防ぎ，安全かつ高精度な切除を実現する．

現在コントローラにはジョイスティックを用いている．コントローラと各自由度の対応関係を Fig.2 に示す．ジョイスティックの前後屈曲をアームの屈曲，左右屈曲をボディの回転に対応させ，ボタンの押し離しによって，カッターの挿入およびドリルの切削を行う．

## 3. 評価実験および結果

### 3.1. マニピュレータ特性評価

マニピュレータの各自由度無負荷状態での精度評価および切除効率を測定した．各自由度の精度を Table1 に示す．デバイスの高い再現性と，肥大前立腺をカバーする広い可動範囲が確認された．

### 3.2. ファントム実験

ゼラチンの前立腺モデルを用いた切除評価を行った．モデルの大きさは一般的な肥大前立腺の大きさ・質量を考慮して，90g 外径 50mm の円柱ゼラチンモデルとし，中心に直径 4mm の尿道にあたる空洞がつくられている．アームを屈曲させモデルを変位しカッターを挿入しモデルの切除を行った．Fig.3 にカッターを二度挿入・切除したモデル断面を示す．本実験では平面的切除を行い，断面における切除面積と，尿道損傷部を測定した．測定結果を Table2 に示す．

従来手技よりも少ない切除量であったが，尿道の圧迫を緩めるのに十分な切除量であり，また尿道部の損傷を大幅に低減出来ることが示された．

## 4. まとめ

本研究では経尿道的前立腺切除マニピュレータを用いた低侵襲切除システムの開発を行った．評価実験によりシステム下において低侵襲かつ十分量の切除を行えることが示された．

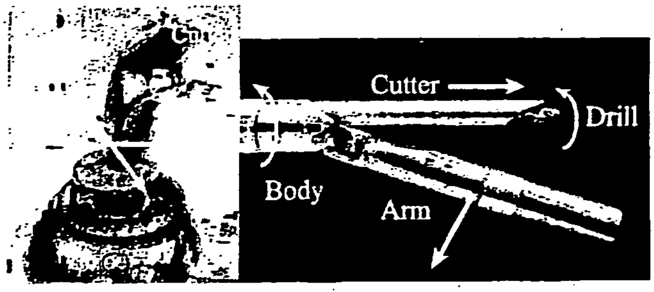


Fig. 2. Correspondence of each degree-of-freedom between master controller and slave manipulator.

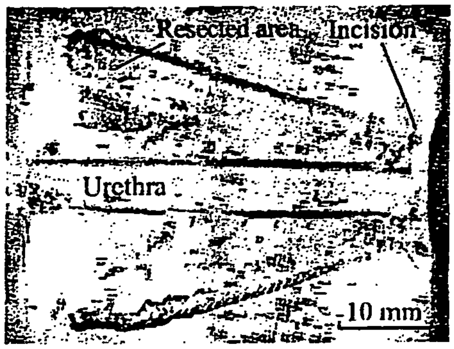


Fig. 3. Cross section of gelatin model. Manipulator could remove tissue through one incision on the urethra model.

Table 1. Accuracy of each degree-of-freedom

| 自由度 | 精度 |
|---|---|
| アーム屈曲 | 0.5 deg. |
| カッター挿入 | 0.2 mm |
| ボディ回転 | 0.7 deg. |

Table 2. Resection performance of manipulator

| | |
|---|---|
| 切除面積 | 589.2 mm$^2$ |
| 尿道損傷部 | 3.7 mm |


**謝辞**

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04(IX)-62

# ウェッジプリズムを用いた視野可変内視鏡の細径化 ＜第1報＞～視野欠損の低減に関する検討～

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## Miniaturization of Wide FOV Wedge Prism Endoscope<1> ~ Reduction of Vignetting ~

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**Abstract:** We developed a novel robotic endoscope system in former study. It can be used to observe a wide area without moving whole endoscope system. Although we confirmed the usefulness and safety not to harm on organic at In-vivo experiments, the 18mm-diameter endoscope is comparatively big for clinical use in fetal, brain, and orthopedic surgery. Therefore, we suggest the miniaturization of a wide-angle view endoscope system using 6mm-diameter wedge prisms. In this study, we report reducing vignetting owing to the miniaturization by adjusting wedge prism's refractive index and endoscope's view angle. We calculated critical view angle by Snell's Law, and measured entire system's global field of view. As a result, the maximum movement of local field of view was 18deg. and global field of view was 91deg.. In addition, we evaluated the resolution and the distortion of the endoscope system.

**Key words:** Wedge prism, Variable field of view, Endoscopy, Medical robot, Minimally invasive surgery

## 1. はじめに

内視鏡下手術において，低侵襲のために内視鏡を円滑に操作するのは非常に重要である．我々は，内視鏡本体を動かさずに鏡筒のみを回転することで，視野の移動が可能な視野可変内視鏡を開発してきた．

これまでに，直径 18mm の視野可変腹腔鏡が製作され，In Vivo 実験の使用に耐えうるものであるという評価を得た．[1)-2)]

しかし，ウェッジプリズムを用いた視野可変内視鏡を胎児外科，脳外科，整形外科などに応用するためにはマニピュレータの細径化が必要である．

そこで本研究では，視野可変内視鏡を細径化する際に生じる視野の欠損を低減するために，ウェッジプリズムの屈折率，硬性鏡の視野角と視野欠損の関係を検討し，硬性鏡の視野臨界角を選定する．また、得られた視野臨界角で構成した視野可変内視鏡の最大視野移動範囲及び内視鏡の視野範囲を測定し，解像度，歪みの評価実験を行う．

## 2. 方法

本視野可変内視鏡は硬性鏡と2枚のウェッジプリズムを用いて視野移動を行う．[1)]

より広い視野範囲を得るためには,ウェッジプリズムの屈折率を高める,視野角の大きな硬性鏡を用いるなどの方法がある.しかし,スネルの法則によると物体の屈折率や光の入射角の関係によって反射が起きる場合があり，視野の一部が欠損してしまう．

$$n_A \sin\theta_A = n_B \sin\theta_B \qquad (1)$$

ウェッジプリズムの屈折率，硬性鏡の視野角を適切に選定することによって視野の欠損のないかつ広い視野の移動が可能である．ここではウェッジプリズムの材料などの面を考えて，屈折率 1.7 のウェッジプリズムを2枚用い，硬性鏡の視野臨界角を計算した．その結果，硬性鏡の視野臨界角は 60deg.であった．Fig.1 に硬性鏡の視野角によるウェッジプリズムでの光の反射，屈折を示す．視野角 60deg.以上の硬性鏡を用いた場合，プリズムBで反射が起き,視野の欠損が生じる．

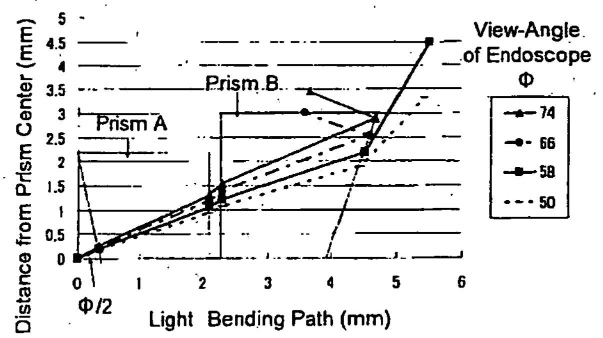


**Fig. 1 Light bending path by wedge prisms**

## 3. 評価実験及び結果

### 3. 1 視野角と視野欠損

硬性鏡の視野角が視野臨界角の 60deg.を超えた場合，視野の欠損が起きる．視野角 55deg.の硬性鏡と視野角 70deg.の硬性鏡を用い，視野欠損の評価実験を行った．

内視鏡先端より 50mm の離れた平面上のチャートの最上部を撮像した．Fig.2 のように視野角 70deg.の場合，視野欠損が起きた．反面，視野角 55deg.の硬性鏡を用いた場合，視野欠損がないことを確認した．

また，最大視野移動範囲及び全体視野範囲を測定した結果，最大視野移動範囲は片側 18deg.（理論値 19.5deg.），全体視野範囲は 91deg.（理論値 94deg.）の結果を得た．

### 3. 2 解像度・歪み

● 解像度

Fig.3 に示す解像度測定用チャートを内視鏡先端から 50mm の平面に置き,撮像した．

視野の向きが中心方向の場合，全体のパターンが明確に見えた．しかし，視野の向きが最も側面左方の場合は 5x5mm のパターンは白黒の職別が不可能であり，10x10mm の場合は多少困難であった．

● 歪み

Fig.4 に示すようなチャートを内視鏡先端から 50mm の平面に置き，歪みの評価を行った．5x5mm 四角形の横長さと縦長さの比を Table.1 に示す．

視野の向きが中心の場合(Fig.4 の(A),(B))歪みがほとんどなく，ウェッジプリズムの無いときと同じであった．しかし，視野の向きが最も側面の場合((Fig.4 の(C),(D)),画面のエッジ((Fig.4 の(D))では 0.60 で，歪みの補正が必要と考えられる．

## 4. まとめ

本研究では，視野可変内視鏡の細径化を目標とし，その第一歩として視野可変内視鏡を細径化する際に生じる視野欠損を低減する方法を検討した．視野欠損のないかつ最大の視野範囲を確保するために，ウェッジプリズムの屈折率，硬性鏡の視野角の関係を最適化した．その結果，本視野可変内視鏡の最大視野移動範囲は片側 18deg.，全体視野範囲は 91deg.であった．また，解像度，歪みの評価実験でその有用性を検証した．

今後は機構の設計にあたって，マニピュレータの細径化及び非滅菌部の分離を行うことによって，胎児外科，脳外科，整形外科などへの臨床応用を目指す．

本研究の一部は，平成 16 年度厚生労働科学研究費補助金，身体機能解析・補助・代替機器開発事業「新たな手術用ロボット装置の開発に関する研究」および平成 16 年度厚生労働省成育医療研究委託事業(16 公-3)による．

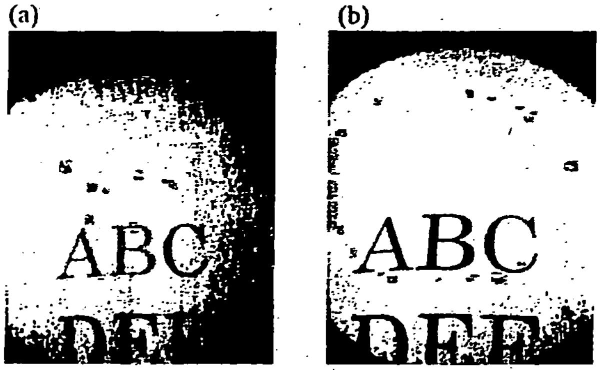


**Fig. 2 Vignetting**
**(a) View angle=70deg.. (b) View angle=55deg..**

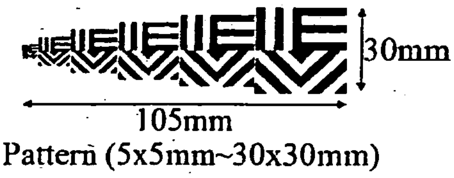


**Fig. 3 Resolution measurement chart**

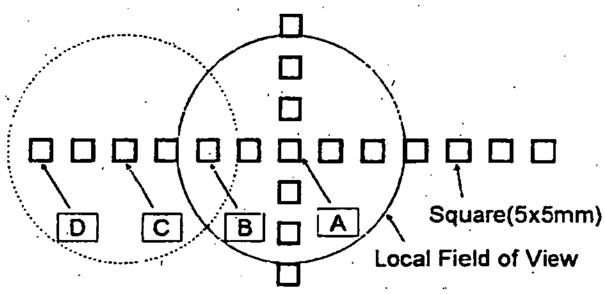


**Fig. 4 Distortion measurement chart**

**Table. 1 Distortion measurement**

| (square, x, y) | | Aspect ratio(x/y) of square at local field of view | |
|---|---|---|---|
| | | Center | Edge |
| Global field of view | Center | 1.00 (A) | 0.96 (B) |
| | Edge | 0.87 (C) | 0.60 (D) |
| Without wedge prism | | 1.00 | 0.96 |

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05(XI)-50

# 多自由度屈曲型バイポーラ電気メスマニピュレータの開発

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# Bipolar Electric Scalpel Manipulator with Multi-DOFs Bending Mechanism

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**Abstract:** This paper proposes multiple functionalizing of multi-DOFs laparoscopic forceps manipulator with maximum power of 0.85 [kgf]. Specifically for more secure, rapid and efficient operations we installed bipolar electric scalpel function into the forceps manipulator to seal blood vessels. Dimension of the electrode we loaded on the forceps blades was 1 [mm] x 5 [mm] x 0.1 [mm] x 2 lines with 0.5 [mm] space to generate high current density between two forceps blades. System integration of this manipulator consisted of multi-DOFs end-effector, linear-drive unit, computer-based control unit, dial-type interface and bipolar coagulator. In vivo experiment, using swine, we approached to mesenteric surface tissue to evaluate the ability of sealing blood vessels, adjusting approach path, output electric power, grasping power and ablation time. In order to confirm whether the blood vessels were sealed or not, we cut ablated tissue and checked leek of blood. This manipulator performed approaching blood vessels from various directions safely, and sealing blood vessels steadily, however, sometimes several ablations made electric shield with coagulated tissues on electrodes, which interrupted effective function. In conclusion we were sure of feasibility of the bipolar electric scalpel function with multi-DOFs bending manipulator for clinical applications.

**Key words:** Bipolar electric scalpel, Multi-DOFs forceps manipulator, Laparoscopic surgery

## 1. はじめに

より低侵襲な腹腔鏡下外科手術の実現のため，著者らはこれまでに2自由度の屈曲機構と1自由度の把持機構を有する多自由度屈曲鉗子マニピュレータを開発してきた．このマニピュレータは腹腔内で自由な方向にアプローチを行なうことができ，臓器の持ち上げや組織・針・糸の強固な把持が可能である [1]．しかしエンドエフェクタとしては把持鉗子機能しか持たないため，多種多用な手術手技への対応は難しい．そこで多自由度を有するマニピュレータのエンドエフェクタに多機能化を加えることにより，術中に使用する術具，腹壁に挿入するポートの本数を低減し，また，術中に術具を交換することの煩わしさを解消し，手術手技の安全性や効率を高めることを目的とする．

あらゆる腹腔鏡下外科手術においては，患部周辺組織の血管処理を安全に，かつ迅速に行なうことが重要である．現在，術中の血管処理には電気メスが頻繁に用いられているが，電気メス機能に多自由度を加えることにより，無理な方向からの処理を防ぎ，また，組織の剥離や凝固，閉塞といった作業を効率よく行なえるようになると考えられる．

本研究では，多自由度鉗子マニピュレータに電気メス機能を追加することで，多自由度屈曲，把持鉗子，電気メスを併せ持つことによる有用性の評価を行なう．特に今回は予備実験として，In vivo 実験にて生体における基本的な手術手技能力の評価を行なったので報告を行なう．

## 2. バイポーラ電気メスマニピュレータ

### 2.1 バイポーラ電極の搭載

バイポーラ電気メス機能の搭載には，最大で 0.85 [kgf] の把持力を有する多自由度屈曲マニピュレータを用いる．電気メスによる組織の焼灼能力は，把持力に依るところが大きいため，この強固な把持力は有利に働くと考えられる．鉗子部に取り付ける電極としては，管状組織の閉塞に最適なバイポーラ電極形状についての研究 [2]や，血管閉塞用として開発された LigaSure™ (Valleylab, USA) [3]を参考にし，**Fig. 1** で示す形状に決定した．電流密度を高めるため，1mm×5mm×0.1mm の電極を 0.5mm 間隔で2列並べ，鉗子部の把持面へと貼付を行なった．

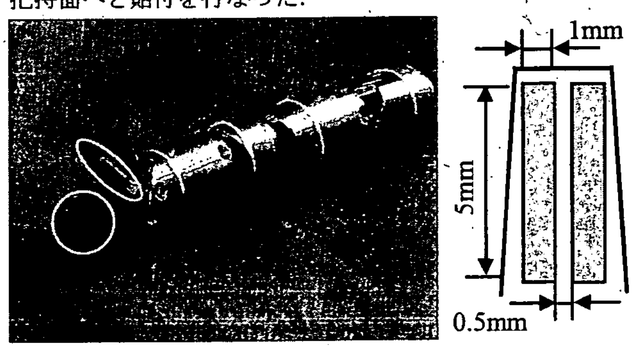


**Fig. 1** Shape of bipolar electrode on the Multi-DOFs forceps blades. Material of electrode is nickel overlaid with gold.

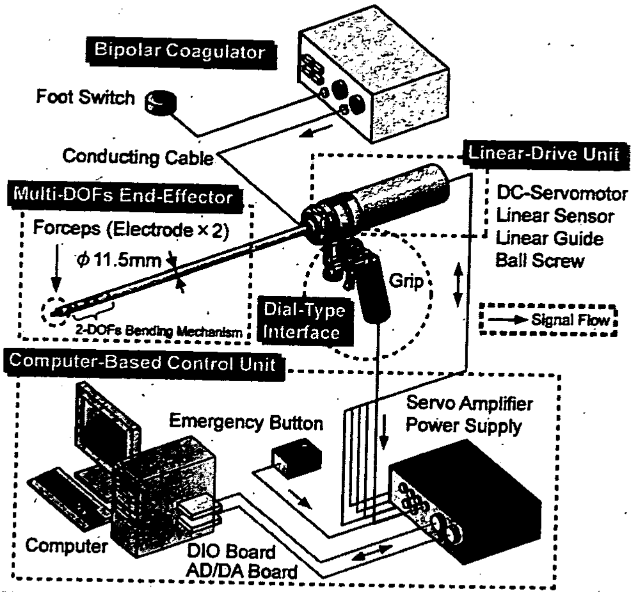


**Fig. 2** System configuration of the bipolar electric scalpel manipulator.

### 2.2 システム構成

**Fig. 2** に本電気メスマニピュレータのシステム構成を示す．基本的な構成は従来のマニピュレータのものを踏襲している．また，電気メスのコアギュレータには瑞穂医科工業株式会社の SS-2100 を用い，焼灼の ON/OFF にはフットスイッチを用意した．

## 3. *In vivo* 実験

動物（ブタ，39kg，オス）を用い，本電気メスマニピュレータの生体における基本的な手術手技評価を行なった．主に血管の閉塞能力を検証するため，焼灼対象に大小の血管が存在する腸間膜を選択した．実験で使用したコアギュレータの設定は，周波数 450 kHz，バースト波使用，繰返し周期 40 μs，デューティサイクル 50 %とし，最終的には電気メスの出力を 20 W まで上げながら数箇所の血管閉塞を試みた．マニピュレータのアプローチ方向，電気メスの出力，鉗子部の把持力，焼灼時間を調整しながら行ない，血管周辺組織の焼灼を行なった後に凝固箇所を切断することで血管の閉塞状態を確認した（**Fig. 3**）．

屈曲自由度をうまく使うことにより，閉塞したい血管組織に対して垂直の方向から無理な力をかけずにアプローチすることが可能であった．1 箇所の閉塞につき 2～3 秒での焼灼を数回行ない，組織の変性を確認した後に凝固箇所を切断した．時間をおいても出血は認められず，完全に血管を閉塞できたことを確認した．

一方，今後改善すべき点としては，(1) 焼灼の繰り返しにより電極上に組織が膜状に付着し，通電効率が低下することがあったため，電極表面に凹凸をつけ，配列を改善する，(2) マニピュレータ本体術中での取り扱いを容易にするため，細径化や小型軽量化，先端の鉗子部に回転自由度の追加を検討する，等が挙げられる．

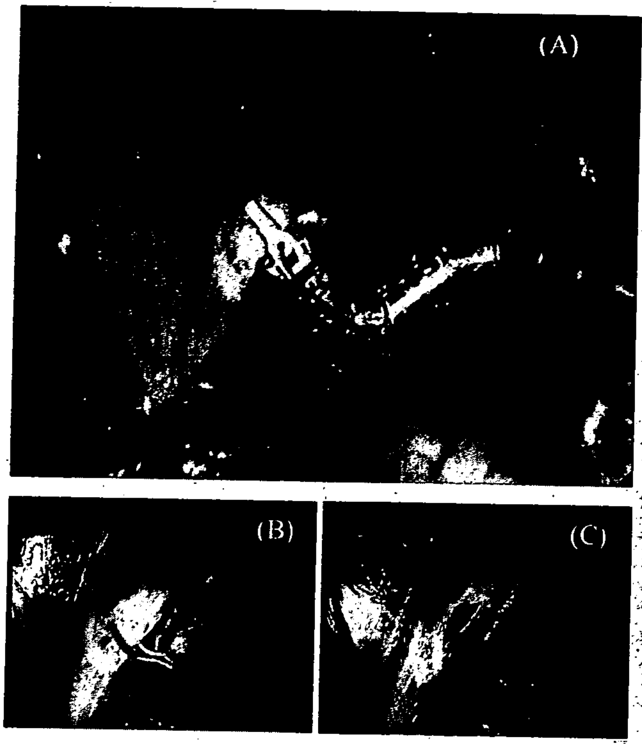


**Fig. 3** Sealing mesenteric blood vessels. (A): Ablation of vessels with 2-DOFs bending motion of the bipolar electric scalpel manipulator. (B) and (C): Confirming vascular occlusion with cutting ablated tissue.

## 4. 結論

本研究ではバイポーラ電気メスマニピュレータの開発を行い，焼灼対象へと自由にアプローチを行ないつつ，血管を閉塞する能力を有することを確認した．今後はより臨床での使用に適したマニピュレータの開発を進めていく．

本研究の一部は，平成１７年度厚生労働科学研究費補助金（身体機能解析・補助・代替機器開発研究事業）「新たな手術ロボット用ロボット装置の開発に関する研究（H15-フィジ-002)」ならびに日本学術振興会特別研究員制度の支援を受けている．

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第14回日本コンピュータ外科学会大会・第15回コンピュータ支援画像診断学会大会合同論文集　pp129-130　千葉　2005

# スライダリンク機構及び空気圧を用いた可撓性外套管のための柔剛可変機構における基礎的検討

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# A mechanism to switch rigid and flexible using slider-linkage mechanism and air pressure for Rigid-Flexible outer sheath

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**Abstract:** In this paper, we report the mechanism that long outer sheath has stiffness and flexibility simultaneously, and switches two modes, rigid and flexible. This outer sheath can become any given shape in flexible mode, and keep its own shape from external force in rigid mode. The outer sheath is able to enter narrow path and holds its shape, and then manages rigid curved path for flexible manipulators to deep, narrow area in human body. Our mechanism consists of multi serial joint model. Each joint rotates freely, and then the outer sheath is able to change its shape, and each joint has one slider that moves in conjunction with the rotation of the joint. When air pressure is added, the slider is locked by the stopper which is in the piece, and then the outer sheath holds its shape. We made the prototype that has 3-pieces model. The diameter of outer frame is 16[mm], and the inner diameter is 7[mm]. We evaluated the relation between the stiffness and air pressure. The outer sheath model switches flexible mode and rigid mode when the air pressure is about 130[kPa]. We confirmed that our mechanism can switch flexible mode and rigid mode, and useful for the rigid-flexible outer sheath.
**Key words:** Rigid-flexible outer sheath, flexible manipulator, slider-linkage mechanism, air pressure

## 1．背景

近年の内視鏡下外科手術の発達により多くの手術が開腹手術に置き換わって行われるようになっている．しかし，この内視鏡手術の問題点として，多くの器具が直線的であるため，気腹，吊り上げ等何らかの方法で術野を確保する必要がある．また体内深部に対するアプローチは困難である．このような問題を解決するためには体内の重要臓器を迂回して侵入することが可能な柔軟なマニピュレータが必要であり，現在開発研究が行われている [1)]．このような柔軟なマニピュレータは途中の重要な組織を傷つけずにアプローチすることが可能であるが，一方で器具自体の体内への挿入，術野への侵入が困難である事が問題となる．このため，あらかじめ器具の進入経路を確保するための機器の開発が求められる．

本研究では進入経路を確保するための機器として，柔剛可変型の可撓性外套管を提案する．これは柔らかい状態で体内へ侵入し，体内で任意の形状で硬くなる．それにより後に手術器具が通過するための経路を確保することが可能となる．本報では提案する外套管が実際に柔と剛の切り替えるための機構を開発し，試作を行った．そして柔と剛に関するそれぞれの特性，及び切り替えに関する評価実験を行ったので報告する．

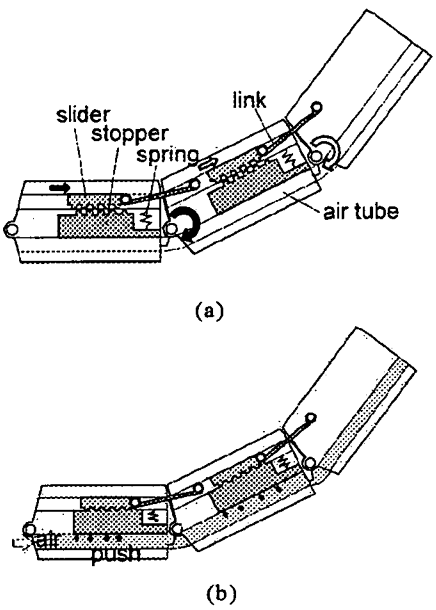


**Fig. 1** Mechanism to switch rigid and flexible: a) flexible mode. b) rigid mode.

## 2．方法

### 2．1　柔剛可変機構

提案する外套管は一定間隔で関節を有しており，それぞれの関節が自由に回転できる．

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スライダリンク機構及び空気圧を用いた可撓性外套管のための柔剛可変機構の基礎的検討
第14回日本コンピュータ外科学会大会・第15回コンピュータ支援画像診断学会大会合同論文集 pp129-130 千葉 2005

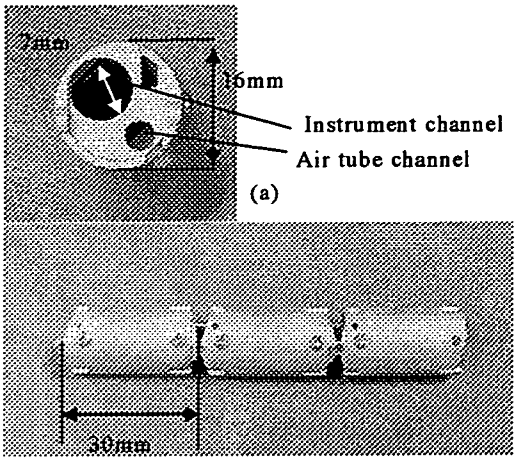


Fig. 2 Outer sheath model: a) cross section image. b) side view.

それにより外套管全体としてさまざまな形状を取ることが可能となる．任意の形状でその形状を維持するための剛性を発生させる方法としては，スライダリンク機構を用いた．それぞれの外套管小片の中にスライダが存在し，関節ごとの回転角度に連動して運動する(Fig. 1a)．このスライダにはラックがついており，外套管小片内に組み込まれたストッパーのラックとかみ合うことでロックされ，全体として形状が固定される(Fig. 1b)．このストッパーを動かす方法として，空気圧による駆動方法を用いた．空気圧を使用することで，伝達させる外套管の形状に依存せずに動力を伝えることが可能である．ストッパーにはバネが組み込まれており，空気を抜くと，元の位置に戻る．

## 2．2 外套管モデル

Fig. 2 に今回試作した外套管モデルを示す．試作した外套管は外形 16mm であり，直径 7mm までの器具を通過させることができる．関節間の 30mm であり，それぞれの関節で±30° の屈曲が可能であり，最小曲率半径は 58mm となる．今回は三つの外套管小片をつなぎ合わせたモデルを作成した．このモデルは二つの関節を有することになる．このモデルでは一平面内での屈曲が可能である．

## 3．評価実験

試作したモデルに対し，本機構の特徴である剛性に関する評価実験を行った．実験方法は一つの

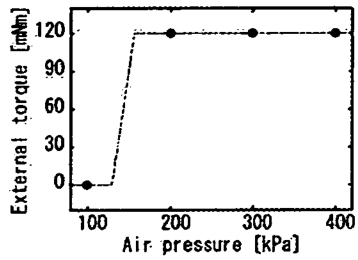


Fig. 3 Relation between torque and air pressure.

関節に対して外力を加え，関節が動くことなく形状を維持できる限界の外力と，空気圧との関係を測定した．Fig. 3 に測定結果のグラフを示す．今回の実験では最大の保持トルクが 120mNm となっているが，これは一関節間隔である 30mm 先で 400gf の力が垂直にかかった場合に相当する．さらに実際はそれ以上の外力にも耐えることが可能であることが予想される．また柔の状態と剛の状態とが切り替わる圧力は 130kPa であった．

## 4．考察・結論

本研究では体内深部へ重要な臓器を迂回して侵入するための経路を確保する方法として，柔剛可変型可撓性外套管を提案し，そのための機構に関する試作を行った．そして，剛性に関する評価を行った結果，一関節分ではあるが 400gf 以上の外力に対して姿勢を保持できることを確認した．これは先端多自由度マニピュレータ [2]が 500gf の発生力を要求しようとし，それ以下でも十分な機能を持っていることから考えても十分な剛性を有するものと考えられる．

## 謝辞

本研究の一部は，平成 16 年度厚生労働科学研究費補助金，身体機能解析・補助・代替機器開発事業「新たな手術用ロボット装置の開発に関する研究」による．

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05(XV)-86

# MR 対応型穿刺ロボットシステムにおける ナビゲーションの基礎的評価

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# Design and evaluation: Navigation in MR-compatible robot system for needle insertion

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**Abstract:** This paper reports the MRI-guided navigation system using robot for horizontal gap open MRI which controls needle orientation effectively in the vertically limited gantry space. We locate the robot including actuators wholly in MR gantry and puncture needle from side of patient's body. We get needle orientation controlled by robot using Polaris, optical position locater and insert the needle to the target tumor displayed on MRI on PC display. In order to realize the navigation system, we acquire the transformation matrices among MRI coordinate system and Polaris coordinate system and among Polaris coordinate system and Robot coordinate system to get transformation matrix among MRI coordinate system and robot coordinate system to control the robot by the tumor location of MRI. We are planning to complete this registration and to measure the precision of needle control under MRI navigation.
**Key words:** MR-compatible Robot, Navigation

## 1. はじめに

核磁気共鳴診断画像装置(MRI)は軟部組織の鮮明な画像が得られる，温度モニタリングが行えるなど利点が多く[1]，Open MRI の登場により，肝臓がん手術におけるマイクロ波凝固療法やラジオ波凝固療法は術中 MRI を用いて，より正確な穿刺と腫瘍の焼灼を行うことが期待できる．

垂直磁場型 MR 対応の腹部穿刺ロボットとして，小型で手術スペースを確保するため，全体をガントリ内に設置したロボットが開発された[2]．本研究では，この開発されたロボットを MRI 誘導下で制御するためのナビゲーションシステムを構築し基本的精度評価を行う．

## 2. 穿刺ロボットと MRI 誘導下ロボット制御

### 2. 1 ロボット仕様

本ロボットは穿刺針を保持し，穿刺経路を決定するために穿刺針の姿勢制御を行うものであり，これらの制御を行うために，5 節リンク機構とジンバル機構を用いた[Fig.1]．

5 節リンク機構は 2 自由度で，リンク先端を 2 次元平面内に位置決めすることができるシンプルな機構で，駆動源をリンク先端の位置決め部から離すことができ，MR 対応性の向上が期待できる点と，駆動部の取り外しが容易で滅菌性に優れている点から採用した．

本ロボットは，5 節リンク機構の駆動に合わせて，穿刺針が回転の 2 方向に姿勢を変化させるため，穿刺針の回転の 2 方向をフリーにした安定した保持が行えるジンバル機構を採用した．

Fig.1 MR compatible robot which holds needle

ロボットの高さは MR ガントリ高さ 420[mm] に対して，最大 240[mm]，5 節リンクの駆動範囲は，superior-to-inferior (S-I)方向に 110[mm]，left-to-right (L-R) 方向に 92[mm]であり，MR 対応性を満たすため，構成材料として，ステンレス・樹脂・セラミックス・アルミニウムを用いた．

### 2. 2 システム構成

MRI 誘導下のロボット穿刺制御のシステム構成図を Fig.2 に示す．

Polaris は MR に取り付けたマーカからの相対位置

として他のマーカの位置を取得することにより，自身が移動に関わらずNeedleの姿勢を取得できる．PCにはPolarisのマーカ位置から計算した針姿勢とMRから得られた画像を表示するとともに，MRI座標系とロボット座標系の変換行列を利用して，MRI上に表示された腫瘍位置から，腫瘍位置をロボット座標に変換し，針を制御して腫瘍への穿刺を行う．

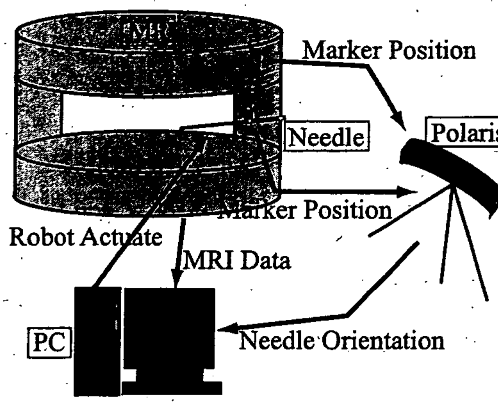


Fig.2 System of MRI guided navigation

## 2．3 MRI誘導下ロボット制御

MRI誘導下でロボットを制御するため，Polarisを用い，①MRI座標系・Polaris座標系変換行列，②Polaris座標系・Robot座標系変換行列を求める．

①を求めるため，格子状にφ6mmの半球状の穴を配置したアクリル製ファントムを製作する[Fig.3]．

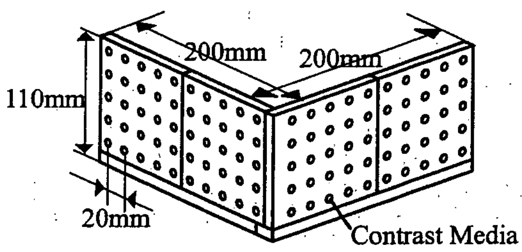


Fig.3 phantom for MRI-Polaris registration

各半球状穴にMRの造影物を挿入し，MRで撮像し，各造影物のMRI上での座標 $\mathbf{X}_{MRI}$ を計測する．次に，造影物を取り除いた半球状の穴を，先端がφ6mmの球状になったPolaris用プローブでポイントし，各半球状穴のPolaris座標 $\mathbf{X}_{Polaris}$ を求める．$\mathbf{X}_{MRI}$，$\mathbf{X}_{Polaris}$ はともに，

$$\mathbf{X}_{MRI}, \mathbf{X}_{Polaris} = \begin{pmatrix} x_1 & x_2 & x_3 & \cdots & x_{100} \\ y_1 & y_2 & y_3 & \cdots & y_{100} \\ z_1 & z_2 & z_3 & \cdots & z_{100} \\ 1 & 1 & 1 & \cdots & 1 \end{pmatrix}$$

と表される．各列は，各造影物の座標を表す．MRI座標系とPolaris座標系間の変換行列を $\mathbf{T}_{MRI\to Polaris}$ とすると，

$$\mathbf{X}_{Polaris} = \mathbf{T}_{MRI\to Polaris}\mathbf{X}_{MRI}$$

となるので，

$$\mathbf{T}_{MRI\to Polaris} = \mathbf{X}_{Polaris}\mathbf{X}_{MRI}^{\#}$$

として変換行列を求める．ここで，$\mathbf{X}_{MRI}^{\#}$ は、$\mathbf{X}_{MRI}$ の擬似逆行列(pseudo inverse)である．

次に②を求めるため，ロボットがPolaris用のマーカ付きの穿刺針を4姿勢に制御し，各姿勢におけるロボット座標系の針先端座標 $\mathbf{X}_{Robot}$ と，マーカの姿勢をPolarisが読み込み，その姿勢から針先端位置を計算することで，Polaris座標系各姿勢における針先端座標 $\mathbf{X}_{Polaris}$ を取得する．$\mathbf{X}_{Polaris}$ と $\mathbf{X}_{Robot}$ はともに各要素が先ほどの $\mathbf{X}_{MRI}$，$\mathbf{X}_{Polaris}$ の各要素と同じ意味を持つ4×4行列である．Polaris座標系とロボット座標系間の変換行列を $\mathbf{T}_{Polris\to Robot}$ とすると，

$$\mathbf{X}_{Robot} = \mathbf{T}_{Polris\to Robot}\mathbf{X}_{Polaris}$$

となるので，

$$\mathbf{T}_{Polris\to Robot} = \mathbf{X}_{Robot}\mathbf{X}_{Polaris}^{-1}$$

して変換行列を求める．

以上で求めた①②の変換行列を掛け合わせることでMRI座標系・ロボット座標系間変換行列 $\mathbf{T}_{MRI\to Robot}$ を求める．

$$\mathbf{T}_{MRI\to Robot} = \mathbf{T}_{MRI\to Polaris}\mathbf{T}_{Polris\to Robot}.$$

## 3 結論

本研究では，垂直磁場型Open MRのスペースの限られたガントリ内で，腹部穿刺用ロボットを用いて，MRIナビゲーション下の制御を実現するための手法を構築した．

今後，開発したMRI誘導下ナビゲーションを用い，ナビゲーション下での穿刺精度を測定し，座標系レジストレーションの有用性，本ロボットの有用性を検証する．

## 4 謝辞

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# Feasibility Analysis of Bipolar Electric Scalpel Forceps Manipulator with 2-DOFs Bending Mechanisms

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*Abstract*— **This paper proposes multi-functionalization of the previously reported laparoscopic forceps manipulator with multi-slider linkage mechanism which enables 2-DOFs horizontal and vertical bending of ±90 degrees and 1-DOF grasping manipulation. Specifically we added a bipolar electric scalpel function on the forceps blades for more safe, speedy and efficient surgical operation with coagulation of tissues and occlusion of blood vessels from various directions in abdominal cavity. This functionalization can lead cutting down the number of surgical instruments and insert ports, and saving troubles of changing tools. For the scalpel function, we mounted a pair of electrodes measuring 1.0 x 5.0 x 0.1 mm x 2 lines aligned with a 0.5-mm space, to generate high current density between two forceps blades. In animal experiment using swine (39 kg, male), we evaluated the ability of occluding blood vessels on mesenteric surface tissues through various directional approach paths using 2-DOFs bending manipulation effectively. We coagulated blood vessels 2-3 times with setting of 20 W and 2-3 seconds energization. And in order to confirm whether the blood vessels were completely occluded or not, we attempted a cut of ablated parts with scissors and checked blood leak. In this experiment we tried to occlude T vessels. Four vessels were occluded successfully, while other two vessel occlusions were incomplete. A little leak was shown in these vessels, however, some repeated coagulation made complete seals. These incomplete coagulations resulted from ablated tissues on the electrodes surface for something of a shield to interrupt effective energization. For the solution of this trouble, it can be effective to improve the electrode and forceps blade shapes. In conclusion, we are sure of feasibility of the bipolar electrode scalpel function with multi-DOFs bending manipulator to ablate tissues and seal blood vessels for laparoscopic clinical applications.**

*Keywords*— **Bipolar electric scalpel, Laparoscopic forceps manipulator, Occlusion of blood vessels**

## I. Introduction

Laparoscopic surgery enables the incision on abdominal wall smaller and makes invasion to patients minimal. For this advantage this surgery is taken in almost all surgery, such as abdominal surgery, chest surgery, orthopedic surgery, brain surgery, obstetrics and gynecology. Surgical instruments such as forceps and electric scalpel are, however, straight-shape thus surgical approaches and manipulations are restricted due to low degree-of-freedom (DOF) instruments through trocars. This inflexibility causes one of the surgeons' mental and physical stress. In order to overcome this issue on limited maneuverability, several robotized devices have been developed to add additional DOFs at the manipulators tip [1]-[3]. Our group developed laparoscopic bending forceps manipulator with multi-slider linkage mechanisms to achieve wide-range 2-DOFs motion at the tip of the forceps in the abdominal wall [4][5]. The linkage-driven approach, unlike recently reported wire-driven mechanisms, enabled sufficient bending power of up to 0.85 kgf, high accurate manipulation of less 1.0 mm, high stiffness and durability. This manipulator performed laparoscopic surgical tasks, such as raising the liver and stomach, stitching and suturing the surface tissues in vivo experiments using swine. However the manipulator had only a forceps function for the end-effector so it was not adaptable enough for a variety of operations.

Therefore we will propose in this paper multi-functionalization of the laparoscopic forceps manipulator to cut down the number of surgical instruments and insertion ports and to save troubles of changing tools so as to improve safety and efficiency of surgical operations for more minimal invasive surgery. In laparoscopic surgery it is significant to do vessel manipulations around the affected area safely and speedy. Current standard electric scalpels are often used for vessel manipulations so it is expected to be useful to combine electric scalpel function and multi-DOF bending mechanism for highly efficient coagulation, exfoliation and occlusion of blood vessels.

This paper reports 1) the addition of a bipolar electric scalpel function on the previously reported laparoscopic forceps manipulator with 2-DOFs bending mechanism, 2) feasibility analysis of this manipulator in vivo experiments to evaluate it for laparoscopic clinical applications.

## II. Materials and Methods

### A. Bipolar Electrode Specification

We mounted a pair of electrodes on the stainless-steel forceps blades surface of the laparoscopic 2-DOFs bending manipulator in order to add a bipolar electric scalpel function. Current standard electric scalpels are for dissection or coagulation, for the former function fine tweezers-type instruments are mainly used in microsurgery. In the meanwhile for the latter function, general forceps-type instruments with properly designed electrodes are often used. Our purpose in this study is to enable dexterous vessel manipulations with multi-DOFs bending motion, therefore we determined the electrodes dimension referring to recently reported studies, such as LigaSure™ (Valleylab, USA) for vessel sealing application [6][7] and the bending forceps manipulator with an electric-cautery function for cystic duct obstruction [8].

Electrodes measurement was 1.0 x 5.0 x 0.1 mm x 2 lines aligned with a 0.5-mm space (Figure 1). Material of electrodes was nickel-based gold, and between electrodes and blades, the insulating resin sheets (glass epoxy) were layered to insulate the electrodes from other components of forceps bending mechanisms. Our manipulator had sufficient grasping power up to 0.85 kgf, thus in case grasping blood vessels and surrounding connective tissues, the gap between electrodes could be so narrow that current efficiency through tissues would be very high.

### B. System Configurations

The system configuration of the bipolar electric scalpel manipulator consisted of mainly five parts (Figure 2). First part was the multi-DOFs end-effector with 2-DOFs bending mechanism and 1-DOF grasping forceps blades with a pair of bipolar electrodes. Second part was the linear-drive unit consisted of three sets of brushless DC-servomotors (FAULHABER GROUP MINIMOTOR SA, 1628 024 B), linear sensors detecting linkage displacements (ALPS ELECTRIC CO., LTD., RDC1014A09), linear-guides (THK Co., Ltd., RSR3WNUU+36L+) and ball-screws (NSK Ltd., M3 x 0.5). Third part was the dial-type interface with three spindle operated potentiometers (Meggitt Electronic Components Ltd., TYPE 51 SERIES), that had two dials for the horizontal and vertical bending operation, a trigger lever for grasping operation and a button for straightening the bending mechanisms in case of getting through a trocar. Fourth part was the computer-based control unit that consisted of a laptop computer (CPU: Intel Pentium M 1.0GHz, RAM: 1GB, OS: Fedora Core 1), a bus bridge including a DIO board (Interface Corporation, PCI-2727) and AD/DA board (Interface Corporation, PCI-3521), and three servo amplifiers (FAULHABER GROUP MINIMOTOR SA, BLD 3502) calculating displacements of sliding two linkages and one stainless-steel wire by inputted target angles from the dial-type interface. And last part was the bipolar coagulator (MIZUHO Co., Ltd., SS-2100) with a foot switch to turn on electricity to the electrodes.

Between the multi-DOFs end-effector and the linear-drive unit we equipped easy linkage connector for cleaning, sterilization before and after operation. At this connector the multi-DOFs end-effector, the linear-drive unit and the dial-type interface were isolated completely so as to protect patients and surgeons from any electric shock.

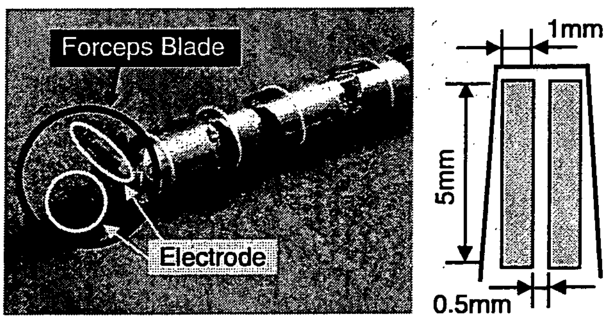


Fig. 1 Shape of bipolar electrode on the multi-DOFs forceps blades.

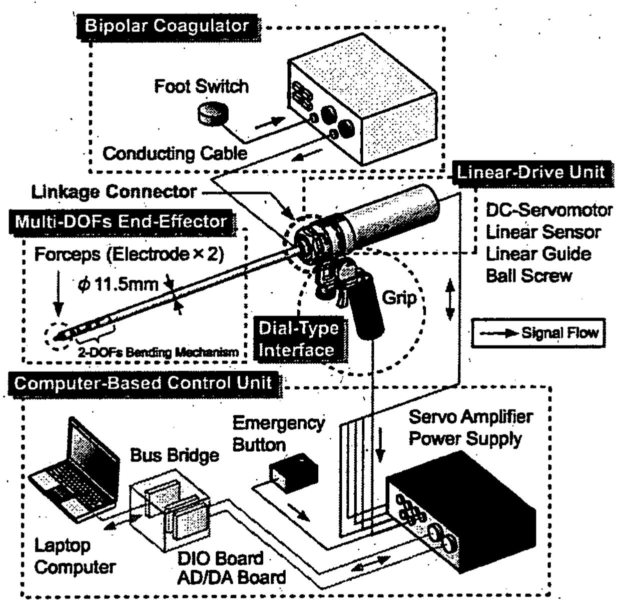


Fig. 2 System configuration of the bipolar electric scalpel manipulator.