Review Articles

Robotic Surgery and Cancer: the Present State, Problems and Future Vision

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In the 1990s, laparoscopic surgery entirely changed the traditional style of surgical operations. Laparoscopic cholecystectomy has spread rapidly and is now established as the standard treatment. However, besides cholecystectomy, endoscopic procedures are still not applied so widely to a variety of surgical operations. This is because laparoscopic techniques, such as suturing or ligation, make it difficult for surgeons to perform other kinds of operations and thus greatly increase their mental and physical stress. It is necessary to introduce various advanced technologies such as: surgical robots, three dimensional (3D) images, computer graphics (CG), computer simulation technology and others. Surgical robots, including the AESOP, da Vinci and ZEUS systems, provide surgeons with technologically advanced vision and hand skills. As a result, such systems are expected to revolutionize the field of surgery. However, there have so far been few studies which discuss the indications of robotic surgery for tumors/cancer. Therefore, herein we review various studies published in English to focus on the application of robotic surgery to tumors/cancer.

We point out that there are several problems to be solved for robot surgery: i) price of surgical robots, ii) training systems for surgeon, iii) coverage by medical insurance, iv) downsizing and v) navigation system. In conclusion, we believe that, in the near future as robotic technology continues to develop, almost all kinds of endoscopic surgery will be performed by this technology. It will replace traditional surgery not only in the treatment of benign diseases but also in malignant illnesses.

Key words: navigation – AESOP – da Vinci – ZEUS – Naviot

INTRODUCTION

In the 1990s, laparoscopic surgery entirely changed the style of surgical operations. The popularity of the laparoscopic cholecystectomy has spread rapidly and it has now become the standard treatment for cholelithiasis. However, the technique has not spread much beyond cholecystectomy, because laparoscopic techniques, such as suturing or ligation, make it difficult for surgeons to perform other kinds of operations, thereby greatly increasing their mental and physical stress. Basically, surgical operations have been developed over the years based on the surgeon's skillful hands and trained eyes.

However, to develop new surgical therapies in the 21st century, it is now necessary to adopt various advanced computer-enhanced technologies; such as surgical robots, three dimensional (3D) images, computer graphics (CG), computer simulation technology and others. 3D images for surgical operations provide surgeons with advanced vision.

Surgical robots, such as AESOP (1–4), da Vinci (5,6) and ZEUS (1–4,7), provide surgeons with technologically advanced vision and hand techniques, which have revolutionized surgery in various fields (see Tables 1–6). The advanced

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Abbreviations: 3D, three dimensional; CG, computer graphics; CAD, computer-aided design; CAM, computer-aided manufacturing; AESOP, automated endoscope system for optimal positioning; IORT, intraoperative radiotherapy; CT, computed tomography; MR, magnetic resonance; MRI, magnetic resonance imaging; FUS, focused ultrasound surgery; CAMIT, Center for Integration of Advanced Medicine, Life Science and Innovative Technology; MIS, minimally invasive surgery; PUMA, programmable universal manipulation arm; LIMA, left internal mammary arteries; LAD, left anterior descending vision and hand techniques now available to surgeons are leading to the development of new surgical fields such as minimally invasive surgery (MIS), non-invasive surgery, virtual reality micro-surgery, tele-surgery, fetal surgery, neuro-informatic surgery and others (8,9).

However, so far there have been few reports which have discussed indications of robotic surgery in the treatment of tumors and cancers. We therefore review here the previous literature to discuss the use of robotic surgery in the field of cancer therapy.

NAVIGATION SYSTEMS

In many surgical fields, including craniomaxillofacial surgery, computer-aided surgery (CAS) based on computed tomography (CT) data is becoming increasingly important. Navigation systems, which allow precise intraoperative orientation of surgical instruments, can be used for greater accuracy in determining the resection margins of target lesions. These techniques also greatly support ablative procedures. However, more complex procedures, such as reconstruction, still remain a problem. Therefore, a computer-aided design (CAD) and computer-aided manufacturing (CAM) system has been developed which allows the construction and fabrication of individual templates for resections based on coherent numerical 3D models (10–12). Iseki and co-workers developed an overlaid three-dimensional image-guided navigation system in neurosurgery, which is able to navigate surgeons accurately during operative procedures (13–15).

In addition, the combination of surgical robots and navigation systems using CT (16), MRI (17) and US (18) will allow us to perform more precise and more minimally invasive gene therapy (e.g. local injection).

SURGICAL ROBOTS

The Master–Slave Manipulator

In general, robotic systems consist of three parts: a surgical cart, a vision cart and the surgeon's console. The surgeon sits at a control console equipped with a display that presents images obtained with an endoscopic camera inside the patient's body. The surgeon's console also provides *master* manipulators, which the surgeon can use to control the movements of the corresponding *surgical* or *patient-side* manipulators (slave manipulator) that hold the surgical instruments and the endoscopic manipulator used for the procedure. The surgeon looks down into the viewer as if looking into the surgical field and at his hands. He holds on to the control handles with his left and right hands. He then carefully guides the tool tips inside the patient's body. As the surgeon moves the manipulators on the surgeon's console, the patient-side manipulators closely follow the input motions.

This master–slave manipulator allows surgeons to perform more precise surgical procedures than those available in conventional endoscopic surgery. A previous study showed that remote-access endoscopic telemanipulation can successfully achieve complex 3D manipulations and the intuitive orientation of the surgeon's workstation may also make such tasks easier to complete (19).

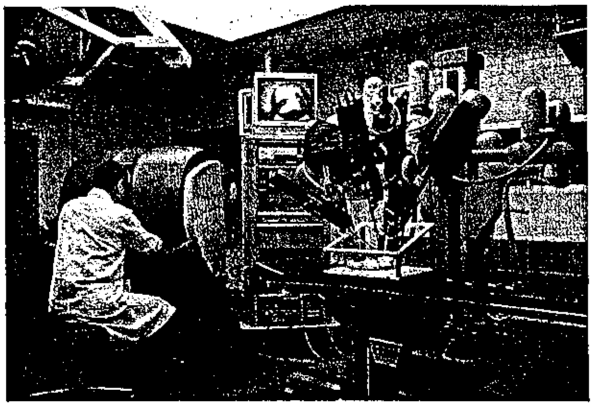

Figure 1. The da Vinci robotic surgical system consists of three parts: (i) the surgeon's console, (ii) an electronic tower holding the video equipment and (iii) the robotic arms.

AESOP®

The first robot approved by the US Food and Drug Administration (FDA) for clinical use in the abdomen was the automated endoscope system for optimal positioning (AESOP) (Computer Motion, Goleta, CA). At the time it was first introduced, the surgeon controlled the robotic arm either manually or remotely with a foot switch or hand control (1,2), but the most recent generation of AESOP is voice controlled (3,4).

da Vinci™

The da Vinci™ Surgical System was developed by Intuitive Surgical (Mountain View, CA). So far, 196 da Vinci systems have been installed worldwide. Many kinds of surgical operations, such as general surgery, urology, cardiothoracic surgery and pediatric surgery, have already been performed using the da Vinci system (see Tables 1–6). This system consists of three main parts: (i) The Surgeon Console, which is controlled by the surgeon: (ii) the Surgical Cart, of which three arms directly perform the procedures; and (iii) the Vision System (Fig. 1). The computer system which controls the whole system resides in the Surgeon Console (5,6). The notable features of the da Vinci Surgical System are as follows: the surgical instruments with the Endo Wrist™ move like human hand motion by artificial articulation and the visualization through a high-quality 3D endoscope is optimal.

This system provides surgeons with (i) an intuitive translation of the instrument handle to the tip movement, thus eliminating the mirror-image effect, (ii) scaling, (iii) tremor filtering, (iv) coaxial alignment of the eyes, hand and tooltip image and (v) an internal articulated endoscopic wrist providing an additional three degrees of freedom.

Regarding the treatment of tumors and cancer, we have successfully performed robotic surgery for esophageal tumors,

Figure 2. The ZEUS robotic surgical system consists of two parts: (i) the video monitor projects a 3D image that can be viewed through glasses mounted with a polarizing filter and (ii) a surgeon sitting comfortably in a chair at the ZEUS console.

thymoma, retromediastinal tumor, gastric cancer and colon cancer using the da Vinci (6).

ZEUS®

Computer Motion, the manufacturer of AESOP®, has also developed the ZEUS® telerobot (7) (Fig. 2). It used AESOP as the foundation for the development of a robot capable of telerobotic surgery. In this system, the voice-controlled robot, AESOP, continues to hold the camera. Two additional AESOP-like units have been modified to hold surgical instruments. The ZEUS system provides almost the same function as the da Vinci, except for the internal articulated endoscopic wrist. Furthermore, ZEUS enables surgeons to perform long-distance remote control surgery using SOCRATES™ (Computer Motion). SOCRATES™ is a surgical telecollaboration system that links remote surgeons directly with colleagues in the operating room. HERMES® (Computer Motion) is the leading-edge operating room's central nervous system. HERMES® enables the surgeon and staff to control a wide variety of networks consisting of AESOP®, ZEUS® and SOCRATES™.

Naviot™

A new system has also been developed recently in Japan called the laparoscope manipulator, Naviot™ (Hitachi, Tokyo, Japan) (20–22) (Fig. 3). This system is recognized as the first surgical robot ever developed in Japan. This manipulator is based on a five-bar linkage mechanism that has two independent motors on the bottom. In addition, the zoom-up mechanism of the laparoscope was applied to this manipulation system. The moving range was about 25° in both the vertical and horizontal directions. As of March 2004, we had performed laparoscopic surgery on 100 patients using this Naviot.

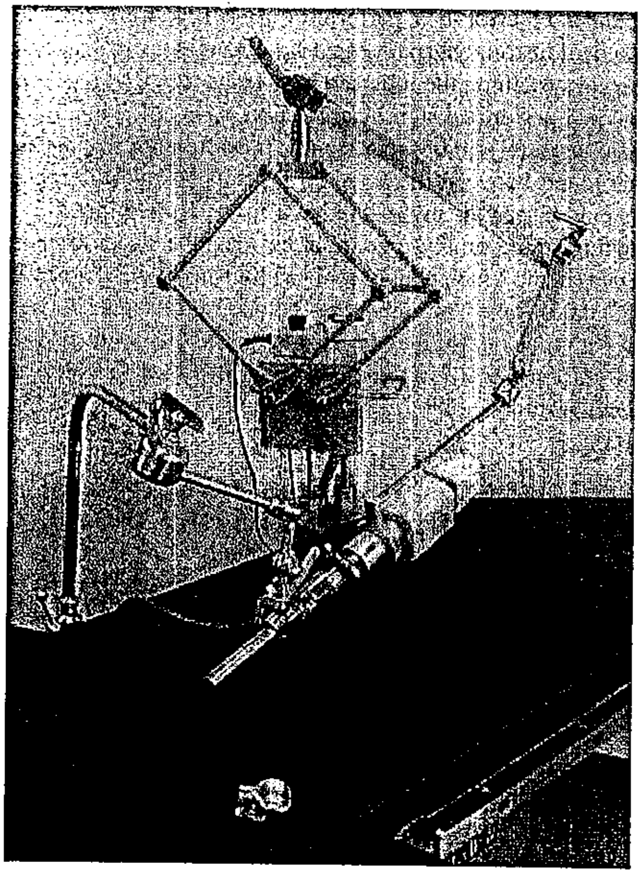

Figure 3. A newly developed laparoscope manipulator, Naviot, is recognized as the first surgical robot developed in Japan.

COMPARISON BETWEEN DA VINCI AND ZEUS

At present, according to two evaluation studies (23,24), the da Vinci system is considered to have some advantages over the ZEUS system.

In an animal study by Sung and Gill (23), during a laparoscopic nephrectomy, the da Vinci system had a significantly shorter total operating room time (51.3 versus 71.6 min; P = 0.02) and actual surgical time (42.1 versus 61.4 min; P = 0.03) compared with the ZEUS system. For a laparoscopic adrenalectomy, the da Vinci system (n = 5) had a shorter actual surgical time (12.2 versus 26.0 min; P = 0.006) than did the ZEUS system. For laparoscopic pyeloplasty, the da Vinci system had a shorter total operating room time (61.4 versus 83.4 min; P = 0.10) and anastomotic time (44.7 versus 66.4 min; P = 0.11). During pyeloplasty anastomosis, the total number of suture bites per ureter was 13.0 for the da Vinci system and 10.8 for the ZEUS system.

In a study by Dakin and Gagner (24), 18 surgeons performed tasks in a training box using three different instrument systems: standard laparoscopic instruments, the ZEUS Robotic Surgical System and the da Vinci Surgical System. The basic tasks included running a 100 cm rope, placing beads on pins and dropping cotton peanuts into cylinders; fine tasks included intracorporeal knot tying and running stitches with 4–0, 6–0 and 7–0 sutures. The time (in seconds) required and precision (number of errors) in performing each task were recorded. Standard instruments performed significantly faster than either robotic system on the rope and bead tasks ($P < 0.05$), whereas da Vinci performed significantly faster than ZEUS in all three basic tasks ($P < 0.05$). No significant difference in precision was found between the standard instruments and the robotic systems regarding any of the basic tasks. Knot tying and the running suture time were similar between the standard instruments and da Vinci, which were significantly faster than ZEUS ($P < 0.05$) for all suture sizes. The robotic systems showed a similar precision for fine suturing tasks and they were also significantly more precise in knot tying (ZEUS and da Vinci) and running sutures (da Vinci) than standard instruments ($P < 0.05$).

ROBOTIC SURGERY FOR TUMORS AND CANCERS

NEUROSURGERY

Neurosurgery is the pioneer and the most active field in robotic surgery. Lunsford reported for the first time the introduction of the gamma knife for brain surgery without making an incision (25). According to this study, the gamma knife was approved for marketing by the FDA in 1982 and the device received approval of the Nuclear Regulatory Commission (NRC) in 1986. Finally, this gamma knife device was first used for patient treatment in 1987 in Pittsburgh, PA (25) and due to this first step, the concept 'brain surgery without an incision' is now a reality.

Drake et al. performed a computer- and robot-assisted resection of thalamic astrocytomas in children (26). Six children ranging in age from 2 to 10 years who had deep benign astrocytomas were operated on using a robot-assisted system and a radical excision was achieved. This system consists of an interactive 3D display of CT image contours and digitized cerebral angiograms which were taken using the Brown–Roberts–Wells (BRW) stereotactic frame. The surgical retractor is held and manipulated using a Programmable Universal Manipulation Arm (PUMA) 200 robot (Westinghouse Electric, Pittsburgh, PA) and the position and orientation of the surgical retractor are shown in the 3D display. Both preoperative planning and simulation are important features of this system. The movement of the brain after removal of the tumor and cerebrospinal fluid is substantial, therefore the tumor removal is based on visually defined margins (26). Carney et al. confirmed that intraoperative image guidance is available in otolaryngology (27). The ISG viewing wand (ISG Technologies, Missasauga, ON, Canada) is an intraoperative guidance system with a proprioceptive robotic-like jointed arm. It provides surgeons with almost instantaneously reconstructed computer-generated CT or MRI images in 2D or 3D which can correlate any points within the operative field to its corresponding locus on the reformatted scan images. In this report, 14 patients with skull-base, cerebello-pontine angle or temporal bone lesions also underwent wand-guided resections. Zamorano et al. reported the application of interactive image-guided resections for cerebral cavernous malformation (28). In their report, 15 patients with cavernous malformations underwent an interactive image-guided resection of their lesions. Diagnoses were made using MRI and digital subtraction angiography (DSA). In addition, an infrared system was used intraoperatively to confirm the location and the extent of the resection in real time. Levesque and Parker confirmed the usefulness of Mehrkoordinaten Manipulator (MKM)-guided resection for diffuse brainstem neoplasms (29). Two patients with extensive brainstem tumors underwent a frameless stereotactic craniotomy using an MKM robotic microscope (Carl Zeiss, Oberkochen, Germany) and intraoperative neurophysiological monitoring. Their result shows that image-guided surgery with an MKM microscope allows surgical outlines to be injected in the microscope viewer, thereby facilitating a resection of extensive brainstem tumors that were previously considered inoperable.

Hongo et al. developed NeuRobot, a telecontrolled micromanipulator system for minimally invasive microneurosurgery, at Shinshu University (30). Using this system, surgical simulations were performed with a human cadaveric head. The system consists of four main parts: (i) a micromanipulator (slave manipulator), (ii) a manipulator-supporting device, (iii) an operation-input device (master manipulator) and (iv) a three-dimensional display monitor. Three 1 mm forceps and a three-dimensional endoscope, which could be remotely controlled with three degrees of freedom (rotation, neck swinging and forward/backward motion), were installed in the slave manipulator. All surgical procedures were accurately performed using this system. Furthermore, the same group showed the usefulness of a potassium titanyl phosphate (KTP) laser with micromanipulators in neurosurgery based on an animal study (31). This system was shown to be capable of performing various surgical procedures including cutting, coagulation and bleeding control compared with conventional systems.

CARDIOLOGY

The da Vinci was specifically designed to perform closed-chest coronary artery bypass grafting (32) (Table 1). As a result, cardiac surgeons have accumulated substantial experimental experience using the da Vinci prototype (33–35). In 1999, Carpentier et al. reported the first successful use of da Vinci for closed-chest coronary bypass grafting (36). Kappert et al. used da Vinci to harvest both the left and right internal mammary arteries for coronary artery bypass grafting in 27 patients (37). Mohr et al. performed coronary artery bypass surgery using da Vinci for 148 patients (38). In brief, they used da Vinci to harvest 81 left internal mammary arteries (LIMA) and then used it to sew 15 LIMA to left anterior descending (LAD) coronary artery bypass grafts through a median sternotomy incision. Following these patients, they constructed 27 LIMA-to-LAD bypass grafts on an arrested heart with a closed chest. More recently, they succeeded in using the da Vinci to anastomose the LIMA to the LAD on a beating heart with a

Table 1. Robotic surgery in cardiac surgery

Disease	Operation
Coronary artery disease	IMA harvest
	Beating heart TECAB (single vessel)
	Arrested heart TECAB (single and multiple vessel)
	Sternotomy LIMA–LAD
	Multi-vessel small thoracotomy bypass
Mitral valve disease	Mitral valve repair
	Mitral valve replacement
Pericardial fluid	Pericardial window
Dilated cardiomyopathy (DCM)	Epicardial lead placement for Bi-V pacing
Aortic ring	Aortic ring dissection
Atrial septal defect (ASD)	Atrial septal defect repair
Aortic coarctation	Resection and reconstruction

closed chest. Autschbach et al. established a mitral valve repair for 13 patients using the same system (39).

Regarding ZEUS, in 1999 Reichenspurner et al. reported its first successful clinical use for coronary artery bypass graft for two patients (40). They harvested LIMA using endoscopic techniques and then sutured LIMA to LAD through three thoracic trocars. The heart was arrested using an endovascular cardiopulmonary bypass system. Later that year, Boehm used ZEUS to successfully perform closed-chest, off-pump coronary artery bypass grafting (LIMA to LAD) in three patients (41). By 2000, the same group had performed coronary artery bypass grafting on beating hearts in 10 patients (42). The total operating time ranged from 4 to 8 h (median, 5.5 h) and ZEUS-assisted anastomoses required 14–50 min (median, 25). ZEUS is also used for a pericardiectomy (43) or mitral valve surgery (44).

However, due to the unique characteristics of heart disease, there have so far been no reports on robotic surgery in the treatment of tumors or cancer.

The Respiratory System

Okada et al. performed a thoracoscopic major lung resection for primary lung cancer by a single surgeon with AESOP and an instrument retraction system (UNITRAC; Aesculap, Tuttlingen, Germany) (45) (Table 2). For a 72-year-old woman with lung cancer, a thoracoscopic middle lobectomy of the right lung with dissection of the mediastinal lymph nodes was successfully performed without human assistance and no complications were observed. Melfi et al. carried out thoracoscopic surgery using the da Vinci system in 12 cases: five lobectomies, three tumor enucleations, three excisions and one bulla stitching completed with fibrin glue for spontaneous pneumothorax (46).

Table 2. Robotic surgery in respiratory and mediastinum surgery

Disease	Operation
Thymoma	Thymectomy
Lung cancer	Wedge resection
	Lobectomy
Upper limb hyperhidrosis	Sympathectomy

Mediastinum

Yoshino et al. successfully performed a thoracoscopic thymomectomy using da Vinci in a 74-year-old male patient who demonstrated thymoma (47) (Table 2). Ruurda et al. reported a thoracoscopic resection of a schwannoma using da Vinci in a 46-year-old female who presented with a left paravertebral mass in the thorax (48).

Breast

In 2000, Kaiser et al. suggested a strong possibility regarding the application of a robotic system for a biopsy and therapy of breast lesions in a high-field whole-body magnetic resonance tomography unit called the ROBITOM (49). ROBITOM [(robotic system for biopsy and interventional therapy of mammary lesions); Institute for Medical Engineering and Biophysics (IMB), Karlsruhe, Germany] consists of a trocar, coaxial sleeve, biopsy needle, laser applicator and a control and drive unit. In this study, *in vitro* experiments on a pig liver including eight targets (vitamin E capsules, 4 mm in diameter) were performed as a model of breast cancer and all eight capsules were hit precisely by this robotic biopsy system. The procedure was performed directly in the isocenter of a 1.5 T whole-body scanner. According to these results, such a robotic system may allow the coordinates of the lesion in the breast to be approached in a high magnetic field. Veronesi et al. showed the usefulness of intraoperative radiotherapy (IORT) in limited-stage breast cancers in 103 patients (50). Because local recurrences after breast conserving surgery occur mostly in the quadrant harboring the primary carcinoma, the main objective of postoperative radiotherapy should be sterilization of residual cancer cells in the operative area, while irradiation of the whole breast may be avoided. They developed a new technique of performing IORT on a breast quadrant after removing the primary carcinoma. A mobile linear accelerator (linac) with a robot arm is utilized delivering electron beams capable of producing an amount of energy ranging from 3 to 9 MeV. Seventeen patients received a dose of IORT ranging from 10 to 15 Gy as an anticipated boost to external radiotherapy, while 86 patients received a dose of 17–19–21 Gy intraoperatively as their whole treatment. This IORT treatment allowed the whole treatment course to be shortened.

Recently, MR imaging-guided focused ultrasound US (MR-FUS) ablation has rapidly developed as a non-invasive treatment for breast cancer (51–53). Gianfelice et al. showed the effectiveness of non-invasive MR-FUS ablation in 12 patients with breast carcinomas (51). In brief, before undergoing a tumor resection, patients were treated with MR-FUS ablation consisting of multiple sonications of targeted points that were monitored with temperature-sensitive MR imaging (Signa™; GE Medical Systems, Milwaukee, WI, USA). The effectiveness of the treatment was determined by a histopathological analysis of the resected mass which was performed to determine the volumes of necrosed and residual tumors. Complications resulting from the procedure were assessed by means of questionnaires, medical examinations and an MR image analysis. US ablation (ExAblate™ 2000; In-Sightec-TxSonics, Haifa, Israel) was well tolerated by the patients and, except for minor skin burns in two patients, no complications occurred. A histopathological analysis of resected tumor sections allowed the quantification of the amount of necrosed and residual tumor and the visualization of the surrounding hemorrhage. In three patients treated with one of the US systems, a mean of 46.7% of the tumor was within the targeted zone and a mean of 43.3% of the cancer tissue was necrosed. In nine patients treated with the other US system, a mean of 95.6% of the tumor was within the targeted zone and a mean of 88.3% of the cancer tissue was necrosed. Residual tumors were identified predominantly at the periphery of the tumor mass, thus indicating the need to increase the total targeted area (51). Huber et al. also revealed the usefulness of MR-FUS ablation in a 56-year-old female who presented with breast cancer (invasive ductal carcinoma) (52). Hynynen et al. also showed the usefulness of MR-FUS ablation for fibroadenoma (53). Eleven fibroadenomas in nine patients under local anesthesia were treated with MR-FUS. Eight of the 11 lesions treated demonstrated a complete or partial lack of contrast material uptake on post-therapy T1-weighted images. Three lesions showed no marked decrease in the contrast material uptake. This lack of effective treatment was most likely due to a lower acoustic power and/or patient movement that caused misregistration. No adverse effects were detected, except for one case of transient edema in the pectoralis muscle 2 days after therapy (53). These papers suggested that (i) invasive ductal carcinoma, (ii) adenocarcinoma, (iii) invasive lobular carcinoma and (iv) fibroadenoma (51–53), were all indications for robotic surgery.

Abdomen

Himpens et al. reported the first successful clinical implementation of telerobotics in March 1997, when they performed a laparoscopic cholecyctectomy using a prototype of the da Vinci (54). The same group also reported a successful use of this system for telerobotic laparoscopic gastric bypass (55), Nissen fundoplication (56,57) and Fallopian tube reanastomosis (58). Other studies showed many kinds of robotic surgery in the abdomen (59–72). Ballantyne and co-workers performed a sigmoid colectomy for diverticulum and right hemicolectomy for cecal diverticulum using da Vinci (59,60) and the operative time for a sigmoid colectomy was 340 min whereas for a right hemicolectomy it was 228 min. The same group also performed the first two cases of ventral hernia repair with mesh (61). Hashizume and co-workers reported the first completely intraabdominal laparoscopic distal gastrectomy for early gastric cancer using da Vinci (6,9). The same group also performed the first gastric devascularization and splenectomy for portal hypertension (6). This report indicates that telepresence technology facilitates these procedures (6,9). Melvin et al. reported a robotic assisted Heller myotomy (67). The same group also performed a pancreatic resection with da Vinci (73). A 46-year old woman presented with back pain and a complex cystic mass in the tail of the pancreas. The da Vinci was used to remove the lesion *en bloc* with the tail of the pancreas and spleen. Marescaux et al. reported a large clinical trial with ZEUS and 25 selected patients underwent ZEUS-assisted laparoscopic cholecystectomies (74).

Regarding the robotic abdominal surgery for cancer (6,8,54–72), an extraction of esophageal tumor, a distal gastrectomy for gastric cancer, an ileocecal resection for cecal cancer, a left hemicolectomy for descending colon cancer, a sigmoidectomy for sigmoid colon cancer, a thymectomy for thymoma and an extraction for retromediastinal tumor have all been performed successfully. As a result, almost all types of tumors or cancers may therefore be indicated for robotic surgery (Table 3).

Urology

Abbou et al. reported on a radical prostatectomy using da Vinci (75). The patient was a 63-year-old man presenting with a T1c tumor discovered on one positive sextant biopsy with a 3 + 3 Gleason score and 7 ng/ml. preoperative serum prostate specific antigen. The da Vinci provided an ergonomic surgical environment and a remarkable dexterity enhancement. The operating time was 420 min and the hospital stay lasted 4 days. The bladder catheter was removed 3 days postoperatively and 1 week later the patient was fully continent. A pathological examination showed a pT3a tumor with negative margins (75). Young et al. reported an adrenalectomy for adrenal incidentaloma using da Vinci (76). In this report, an incidental left adrenal mass was found in a patient during an evaluation for mediastinal widening. The patient had no symptoms attributa-

Table 3. Robotic surgery in general surgery

Disease	Operation
Esophagus	
GERD	Nissen fundoplication
Esophageal achalasia	Heller myotomy
Esophageal cancer	Esophagectomy
Esophageal mass	Esophageal mass enucleation
Stomach	
Gastric cancer	Gastric bypass
	Gastrectomy
	Gastric jejunostomy
	Gastric resection
Colo-rectal	
Colon cancer	Hemi colectomy
	Colon resection
	Sigmoidectomy
Rectal cancer	Low anterior resection (LAR)
Rectal tumor	Rectal tumor ablation
Rectal prolapse	Rectopexy
Appendicitis	Appendectomy
Hepato-Biliary-Pancreas	
Cholelithiasis	Cholecystectomy
Pancreas cancer	Pancreaticoduodenostomy (PD)
ITP	Splenectomy
Others	
Lymph node metastasis	Lymph node dissection
Inguinal hernia	Herniorrhaphy
Acute abdomen	Diagnostic laparoscopy
Arteriosclerosis obliteration (ASO)	Illeo-femoral bypass
	Aorto-femoral bypass
Painful disc disruption (PDD)	Anterior lumbar interbody fusion (ALIF)

Table 4. Robotic surgery in urology

Disease	Operation
Kidney	
Renal ptosis/floating kidney	Nephropexy
Renal failure	Donor nephrectomy
Renal cyst	Renal cystecomy
Renal cancer	Nephrectomy
	Vasovasostomy
Adrenal gland	
Adrenal adenoma	Adrenalectomy
Ureter	
Ureteropelvic junction (UPJ) stenosis	Pyeloplasty
Uninary bladder cancer	Pelvic lymphadenectomy
Ureterovesical junction (UVJ) stenosis	Ureteroplasty
Ureteral cancer	Ureteroureterostomy
	Urethral implant
	Ureterectomy
Urinary bladder	
Atrophic bladder, neurogenic bladder	Bladder augmentation
Urinary incontinence	Bladder neck suspension
Prostate	
Prostate cancer	Prostatectomy

Table 5. Robotic surgery in gynecology

Disease	Operation
Uterine	
Uterus cancer	Hysterectomy
Ovary	
Patients who are to undergo pelvic radiation	Ovarian transposition
Patients who underwent a previous tubal ligation	Tubal reanastomosis

ble to adrenal excess. Preoperative biochemical screening was negative for a functioning medullary or cortical adrenal tumor. A surgical resection was successfully completed with the assistance of the da Vinci robotic system. Pathology demonstrated a rare adrenal oncocytoma (76). Recently, in kidney transplantation, a donor nephrectomy has also been performed using the da Vinci (77,78).

Guillonneau et al. reported ZEUS-assisted laparoscopic pelvic lymph node dissection in humans (79). Robotic-assisted laparoscopic pelvic lymph node dissection was performed in 10 consecutive patients with mainly T3 M0 prostatic carcinoma (robotic group). All operations were performed according to the established protocol with no specific intraoperative or postoperative complications. No conversion was required and no technical incidents were observed.

The indications of robotic surgery for cancer/tumor are renal cancer and prostate cancer (Table 4).

Gynecology

Mettler et al. tried the use of AESOP in 50 patients undergoing routine gynecological endoscopic surgical procedures and AESOP allowed two doctors to perform complex laparoscopic surgery faster than without the robotic arm (80) (Table 5). Diaz-Arrastia et al. reported robotic hysterectomy and salpingo-oophorectomy for 11 patients (81). Molpus et al. reported the first clinical case of robotically assisted endoscopic ovarian transposition using da Vinci (82). Ovarian transposition is the anatomical relocation of the ovaries from the pelvis to the abdomen. Transposition is beneficial in women who are scheduled to undergo pelvic radiation, because it allows the maintenance of ovarian function and preservation of assisted reproductive capacity. In such cases, it is possible to perform ovarian transposition using the da Vinci system (82).

Regarding robotic surgery, Margossian and co-workers explored the applications of ZEUS in gynecology, using exper-

Table 6. Robotic surgery in pediatric surgery

Disease	Operation
Gastrointestinal	
Gastroesophageal reflux disease (GERD)	Pyeloplasty Nissen
Hirschsprung disease	Colectomy
Hepato-biliary	
Cholelithiasis	Cholecystectomy
Idiopathic thrombocytopenic purpura (ITP)	Splenectromy
Urology	
Multicysplastic kidney (MCK)	Nephrectomy
Vesicoureteral reflux (VUR)	Ureter neocystostomy
	Ureter implant
MCK, megaureter	Ureterectomy
Adrenal cancer	Adrenalectomy
Undescended testis	Orchiopexy
Urinary incontinence	Bladder neck suspension

imental models (83,84). They demonstrated that uterine horn anastomoses in six pigs sutured using ZEUS were all patent 4 weeks after surgery (83). This study highlighted the potential role of robotics for microsurgery. The same group also used ZEUS to perform five hysterectomies in pigs (84), where the mean surgical operating time was 200 min. Regarding the AESOP system, a laparoscopic robot-assisted ovariectomy was performed for ovarian serous cyst (85). Falcone et al. used ZEUS to perform tubal reanastomosis for 10 patients with previous tubal ligations who underwent a laparoscopic tubal ligation (86). The procedure was completed successfully in all 10 patients, none of whom required conversion to an open procedure. A postoperative hysterosalpingogram demonstrated patency in 17 of the 19 (89%) tubes anastomosed and there have been five pregnancies so far (86).

In gynecology also, the MR-FUS has been used to perform operations for uterine leiomyomas (87) and fibroid tumors (88). According to Tempany et al., the eligibility criteria for enrollment were as follows: adult women (age >18 years), premenopausal status with a uterine size of <20 weeks and no dominant leiomyoma >10 cm in diameter (87). MR-FUS was performed successfully in nine women (age range, 39–51 years; mean, 43.4 years) with symptomatic leiomyomas and a hysterectomy was done 3–30 days after MR-FUS as evaluation of its effect.

Pediatric Surgery

The use of robotic surgery has also become widespread in pediatric surgery (89–93) (Table 6). Gutt et al. performed Thal and Nissen fundoplication for GERD, a cholecyctectomy for cholecystolithiasis and bilateral salpingo-oophorectomy for gonadoblastoma using da Vinci for 11 children with a mean age of 12 years (range, 7–16 years) (89). The mean operating time for fundoplication was 146 min, whereas for a cholecystectomy it was 128 min and for a salpingo-oophorectomy it was 95 min and no complications were observed (89). Bentas et al. performed an adrenalectomy for benign adrenal tumors using da Vinci (90). The same group reported pyeloplasty for ureteropelvic junction obstruction (UPJO) using da Vinci (91). In experienced hands, a laparoscopic pyeloplasty is an effective alternative treatment for symptomatic UPJO. Although laparoscopic surgery can clearly benefit patients, laparoscopic pyeloplasty using conventional instrumentation is complex. Eleven pyeloplasties for UPJO were performed via a laparoscopic transperitoneal approach exclusively with the da Vinci. The mean procedure time was 197 min (range, 110–310 min). All operations were completed laparoscopically with no intraoperative complications and negligible blood loss. All patients recovered rapidly after surgery with excellent functional results at the 1 year follow-up. Their initial experience suggests that robot-assisted Anderson–Hynes pyeloplasty is a safe and effective alternative to conventional laparoscopic surgery (91).

Le Bret et al. reported the possibility of robotic surgery for pediatric heart disease (92). Fifty-six children weighing from 2.3 to 57 kg (mean, 12 kg) underwent a surgical closure of a patent ductus arteriosus. They were divided into two groups, one consisting of 28 patients (group 1) who underwent videothoracoscopic techniques and the other of 28 patients (group 2) who underwent a ZEUS-assisted approach. The operating time was significantly longer in the robotically assisted group. One conversion in videothoracoscopy was necessary, but no thoracotomy was required. Three persistent shunts were detected at postoperative echocardiography and were treated by applying a new clip with videothoracoscopy (one in group 1 and two in group 2). No permanent laryngeal nerve injury and no hemorrhage were noted. The mean hospital stay was 3 days in both groups.

Dermatology

In 1988, Rotteleur et al. reported a robotized scanning laser handpiece for the treatment of port wine stains and other angiodysplasias (94). This system is made of a handpiece with a scanning mechanism and a control box with a microprocessor. The system is independent of the laser (no electrical connection) and has its own power meter. The deposit of energy was optimized for effective heat diffusion in the skin. A total of 123 patients were treated with the robotized handpiece and no hypertrophic scars were reported. McDaniel reviewed laser treatment for benign cutaneous vascular disorder in children (95) and showed that automated robotic laser scanning devices allow faster, less painful and more cost-effective treatment.

Handels et al. showed an approach to computer-supported recognition of melanoma based on high-resolution skin surface profiles (96,97). In brief, profiles are generated by sampling an area measuring 4 × 4 mm^2 at a resolution of 125 sample points per mm with a laser profilometer at a vertical resolution of 0.1 μm. This new image analysis and pattern recognition method make it easier and more accurate to treat skin tumors (96,97).

CAPSULE ENDOSCOPY

Since Iddan et al. developed a new wireless capsule endoscopy named device M2A™ (Given Imaging, Yoqneam, Israel) in 2000 (98), this new endoscopy system has been shown to have an excellent diagnostic ability for small bowel disease, bleeding and chronic abdominal pain (99–107).

Small bowel imaging is important in the evaluation of obscure gastrointestinal bleeding (108), inflammatory disease of the small bowel (109) and tumors. The main methods of small bowel imaging have been either enteroscopy or small bowel barium studies for evaluating the luminal pathology. Angiography is a diagnostic option in the context of suspected small intestinal bleeding. Push enteroscopy allows an examination of only 80–120 cm of the small bowel beyond the ligament of Treitz, while intraoperative enteroscopy requires general anesthesia and a laparotomy. Small bowel series and enteroclysis have limited sensitivity and, in particular, could not detect flat lesions such as angiodysplasia (110). Therefore, wireless capsule endoscopy has been applied for many kinds of small bowel diseases (99–107).

Regarding the system of capsule endoscopy, in brief this system comprises the following components: a 26 × 11 mm M2A capsule which contains a miniscule color video-camera equipped with a localization feature, a data recorder which is portable, battery-operated external receiving/recording unit that receives data transmitted by the capsule and subsequently allows data downloading and a Rapid Workstation, a modified personal computer which has been designed for storage, the processing and presentation of captured images and the generation of reports (99–107).

PROBLEMS

There are several basic problems that remain to be resolved in order for robotic surgery to spread more widely: (i) the price of surgical robots, (ii) training systems for surgeons, (iii) medical insurance cover, (iv) downsizing and (v) navigation systems. Regarding the price of robotic systems and medical insurance cover, the success of laparoscopic surgery over the past 10 years would endorse further use of robotic surgery (111,112). Regarding the training systems for surgeons, an excellent report on the significance of training has been published (113). Furthermore, our group at the Center for Integration of Advanced Medicine, Life Science and Innovative Technology (CAMIT) of Kyushu University (http://www.camit.org) started a training course called 'Hands-on Training for Robotic Surgery at Kyushu University' in July 2003. There are two training courses for robotic surgery. One is a one-day inanimate laboratory course and the other is a two-day course with animate laboratory. Both courses are open not only for medical doctors, but also for wider ranges of researchers in engineering in both academia and industry.

THE FUTURE

Regarding clinical applications, we envisage that almost all surgery can and will be performed by robotic surgery in the future. For that to happen, the following systems should be developed further: (i) an image-guided surgical assistant system, (ii) smaller sized forceps for robots, (iii) capsule endoscopic surgery and (iv) a surgical robotic system. In education and training, training centers for robotic surgery, such as our institute CAMIT, should be established around the world.

CONCLUSIONS

We believe that in the very near future, thanks to the rapid and continuing development of robotic technology, almost all kinds of endoscopic surgery and thoracoscopic/laparoscopic surgery will become performed by robotic surgery, not only for benign disease but also for malignant illnesses.

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解説

手術支援ロボットの現状と将来

Surgical Robotic System

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1. はじめに

患者に優しい低侵襲治療を求めて，外科治療は大きく変わろうとしています [1]．低侵襲治療の目的は，小さな傷口で従来と同等ないしはそれ以上の治療効果で病気を治し，術後の痛みを少なくして，早期に回復させ，早期社会復帰を図ろうとするものです．すなわち，患者の Quality of Life (QOL，生活の質）を重視した治療法といえます．

低侵襲治療法には，遺伝子治療や分子標的療法，再生医療，内視鏡的治療など様々な分野が含まれます．手術支援ロボットは，これらのうち内視鏡的治療の延長上に位置づけられるもので，コンピュータを用いて人間にはできないより精密な操作や，アクセス困難な場所でのアプローチを可能とします．結果として，より効果的で，安全な治療の達成を支援します [2]~[4].

2. 内視鏡下外科手術の限界

一般外科領域において，1990年代より全世界で爆発的に普及した内視鏡下外科手術は，患者にとって負担が少なくかつ早期回復が見込め，入院期間も短く医療経済的にもコストの削減に貢献できることから，現在では一般外科手術の約30%以上が内視鏡的に治療される時代となりました．胆嚢摘出術では実に95%以上が内視鏡的に行われています．

しかし，現状の内視鏡下外科手術は，限られた狭いスペースで自由度の少ない鉗子を用いて操作せざるを得ず，開腹術のように術者の思い通りに手術を行うことは極めて困難といえます．したがって，入念な術前計画と，十分な開腹術での経験や内視鏡下外科手術の訓練なくしては，手術ミスや術中合併症を起こす可能性が高いといわざるをえません．

3. 技術的困難の克服

内視鏡下外科手術の現状の問題点を打破するためには，
(1) 鉗子の自由度をあげる
(2) 内視鏡の視野や解像度をあげる
(3) 力覚や触覚情報を提供する
などがあげられますが，今後未来型医療を実現するためには，
(1) 従来，外科医の手ではできなかったことを可能とする (super-hand)
(2) 従来，外科医の目では見えなかったものを可視化する (super-vision)．ヴァーチャルリアリティの実現
(3) 生体情報をオンデマンドで，リアルタイムに提供する
などの新しい技術革新が必要と考えます．

外科の基本手技である把持，剥離，結紮，切離，切除などの操作を解析し，真の目的達成のために新たな観点から鉗子や内視鏡の能力や機能を見直す必要があります．

4. 手術支援ロボット

前述の内視鏡下外科手術の技術的な問題点を解決する方法の一つが，この手術支援ロボットです．患者と外科医の手や目の間にコンピュータ機能を備えたインターフェースが介在し，従来の手法よりもより確実で，安全に手技を完遂することを支援します．現在，世界中で臨床応用されている手術支援ロボットとしては，ゼウスやダビンチなどがあります．

(1) ナビオット

ナビオット（図1）は，腹腔鏡把持支援ロボットで，日本学術振興会未来開拓学術研究推進事業で開発した技術を用いて製作されました．2002年に厚生労働省より医療用具と

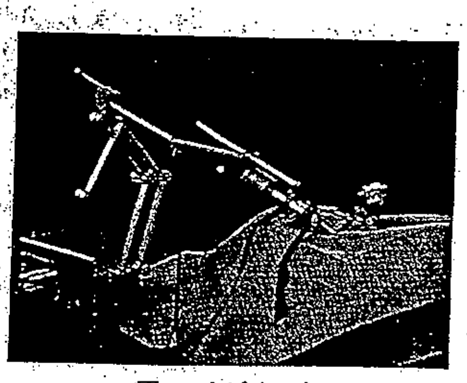

図1 ナビオット

原稿受付 2004年3月30日
キーワード：da Vinci, ZEUS, Naviot, Navigation System, Simulation System
*〒812-8582 福岡市東区馬出 3-1-1
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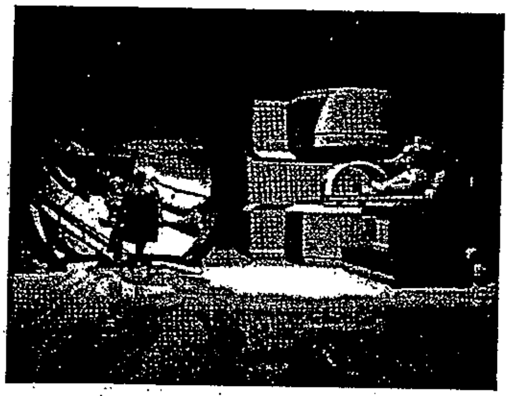

図4　画像誘導下手術支援ロボット

図5　ナビゲーションシステム（腹腔鏡下肝切除時における術前の3Dバーチャルイメージ）

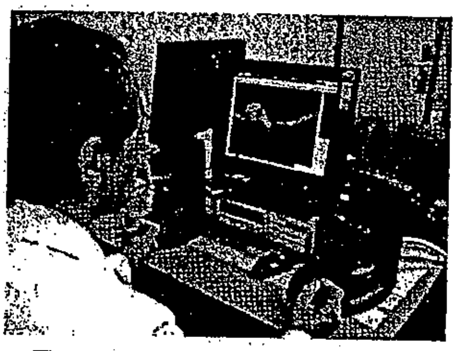

図6　手術シミュレーションシステム

テム（図5）や，多自由度および多機能鉗子の開発も行っています．

(6) 外科医の新たな教育システム

内視鏡下外科手術は，今後ますます普及し，その適応範囲も広がっていくことが予想されます．また，ロボット手術は，その発展に不可欠のものといえます．実際に，お腹を開けたことがない外科医が今後増えることを考え，我々は，東京慈恵会医科大学鈴木直樹教授と手術シミュレーションシステムを開発しています（図6）．これは，コンピュータ上で手術のトレーニングを行うことを可能とするものです．

また，九州大学病院先端医工学診療部では，日本内視鏡外科学会と日本コンピュータ外科学会の後援を得て，国内外の外科医や工学系研究者を対象とした，ロボット手術のトレーニングセミナーを毎月2回開催しています（図7）．

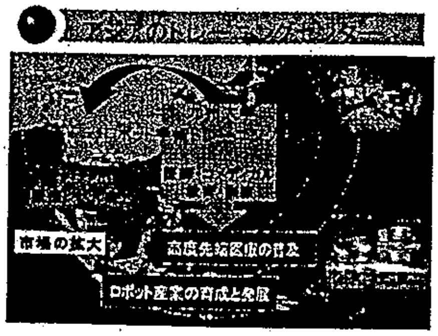

図7　ロボット手術トレーニングセンター

6. お わ り に

世界のロボット手術は，すでに臨床応用開始のときを過ぎ，普及の時代に入っています．21世紀は，患者に優しい医療が目標です．主体は，患者にあります．外科医の自己満足に終わってはいけません．傷口が小さいだけの内視鏡下外科手術に留まることなく，より侵襲の少ない，かつ，より効果的な治療法を開拓していくことこそ今我々に課された課題であります．

日本ロボット学会の会員である皆様とともに新しいページを開くことができることを願っています．

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1984年九州大学大学院医学研究科博士課程修了．医学博士．1998年九州大学医学部第二外科助教授を経て，1999年九州大学大学院医学研究科災害救急医学（後に大学院医学研究院先端医療医学部門災害救急医学分野に名称変更）教授就任．2003年九州大学病院先端医工学診療部長併任．現在，消化器外科，門脈圧亢進症，ロボット医学，低侵襲治療学，災害救急医学などの研究に従事．低侵襲治療に興味を持つ．第41回日本消化器外科学会会長賞（1993年2月），2003年度日本ロボット学会実用化技術賞受賞．日本外科学会，日本救急医学会，日本コンピュータ外科学会（理事），日本腹部救急医学会（理事），日本門脈圧亢進症学会（評議員），日本消化器外科学会（評議員），日本消化器内視鏡学会（評議員），日本肝臓学会（評議員）ほかに所属．

04(SS)-9 日本発手術ロボット開発の現状と未来：「臨床応用」

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Present and Future on Development of Surgical Robotic System in Japan

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Abstract: Minimally invasive surgery (MIS) has explosively developed all over the world. It offers the patients less blood loss during the surgery, less pain, and earlier recovery to normalized activity. However, MIS is both physiologically and psychological very stressful to the surgeons. They have encountered greater amount of technical difficulties in MIS than in conventional open surgery. Computer-assisted surgery has emerged with a possibility of overcoming the technical difficulties. Clinical trials have demonstrated the safety and efficacy of the minimally invasive robotic surgery in Japan. However, many regulations are still remained to be solved to advance the minimally invasive robotic surgery. I would like to stress to develop an image-guided precision surgery in the future.

Key words: Robotic surgery, Precision surgery, Image-guided surgery

1. はじめに

我が国の手術支援ロボットの開発は、順調に進んではいるものの、残念ながら臨床応用の方は欧米に比べ格段の遅れを取り始めている。従来、診断器機分野では世界をリードしながら、治療器機分野での研究開発が遅れていることが指摘されてきた。我が国の手術ロボット開発の現状とその問題点、さらに今後に期待する未来像について述べる。

2. 欧米での実用化

手術支援ロボット、ダビンチ（Intuitive Surgical社、米国）を例にとると、本来、米軍の最前線で兵士が負傷した際に医療班のトラックの中に手術支援ロボットを搭載し、後方病院から遠隔で負傷者を治療することを想定して手術支援ロボットの開発が進められていた。創設者である外科医の Fred Moll やエンジニアの Robert Young は Stanford 大学のこれらの手術支援ロボット開発の技術を元に 1995 年にベンチャー企業である Intuitive Surgical 社を設立しダビンチを完成した。その後、IBM や MIT(Massachusetts Institute of Technology)の技術を導入、さらに今日では、Johnson & Johnson やオリンパス光学、メドトロニクスなどと技術提携を行い、“ダビンチ”はさらに進化している。

昨年、同じく手術支援ロボット“ゼウス”を開発した Computer Motion 社が Intuitive Surgical 社に吸収合併され、世界の市場を Intuitive Surgical 社が独占した格好になっている。

医療用具認可までの期間

ここで注目すべき点は、ベンチャー企業の立ち上げに約 100 億円の資金を集めていることと、起業してから欧州の CE Mark や米国 FDA の承認をとるまでの経過が極めて早い点である。我が国でベンチャー企業を起こすとしても 1 億円もの資金を集めるのは極めて困難である。

さらに、日本では、治療用具として厚生労働省からの承認を得るためには何年かかるか予測できない点にも問題がある。ダビンチは、4年後には CE Mark、5年後には腹腔鏡下手術に関して FDA の承認を獲得し、今年には冠動脈バイパス術の承認を取得した。これによってすべての胸腹部の内視鏡下外科手術が可能となった。FDA の承認は、国内外の市場拡大に拍車をかけ、米国企業を中心とするロボット手術産業の発展に大きく寄与するものと考える。

世界のダビンチ設置台数 243 台

今年 4 月の時点で世界中に設置されたダビンチの台数はすでに 243 台に上っている。この内訳は、米国 171 台、欧州 51 台で、その他の国では、日本 2 台（九州大学、国立循環器病センター）、シンガポール、台湾、インド、サウジアラビア、オーストラリア、カナダ、ルーマニアなどに各 1 台が設置されている。手術症例も心臓外科領域から、一般外科、泌尿器科、産婦人科、小児外科に至るまでほぼすべての内視鏡下外科の術式に応用され、総手術症例数は世界中ですでに一万例以上に上っているが、ロボットに起因する合併症の報告は 1 例もない。心臓手術が開胸せずに手術できることは、外科学の革命である。米国ヘンリーフォード病院では、前立腺全摘出術 1200 例以上にダビンチ手術が行われている。欧米の主な病院では、臨床機とトレーニング機各 1 台、または臨床機 2 台を導入している所もある。

診療報酬

このように、欧米を中心としたロボット手術は、日常診療にルーチンに用いられている。手術支援ロボットは、内視鏡外科手術の一つの治療用具であり、コンピュータ付き高精度鉗子を用いることにより、より高度の、質の高い医療を患者に施すためのツールであるとみなされているのが特徴である。

診療報酬は、ロボット手術という全く新しい手術としてではなく、従来の内視鏡外科手術として請求できる。病院としては、現時点では加算はとれないが、従来よりも多くの患者が受診し、より質の高い医療を施せることがその病院にとってのメリットになっている。

トレーニングシステム

米国では、ロボット手術を開始する前に、FDA が認めた病院でロボット手術のトレーニングを受けることになっている。腹部手術、胸部手術、泌尿器科手術、心臓外科手術の４つのカテゴリーにわけてそれぞれ指定の病院に設置してあるトレーニング用ダビンチを用いてトレーニングをうける。

トレーニングは Intuitive Surgical 社のトレーナーと、指定された病院の外科医によって所定のカリキュラムの訓練を約２－３日間受ける。訓練内容は、ロボットの仕組みや名称、操作方法、安全システムなど多岐にわたり、実技を中心に行われる。

MIRA の設立

このように、欧米では臨床応用が活発に進んでおり、今年 10 月の米国外科学会（ニューオーリンズ）開催に合わせて、Minimally Invasive Robotics Association (MIRA)が設立され、第一回の国際会議が開かれた。MIRA 設立の目的は、ロボット手術に関与する外科医や医療従事者間の情報交換と、一般外科医への普及、市民への啓蒙を意図したものである。

会長には、米国 Hackensack 病院の外科医 Ballantyne 教授が就任した。本会は、毎年定期的に開催し、ロボット手術関連の論文の雑誌への掲載を促進するねらいもある。

３．我が国のロボット手術の現状

世界のロボット市場は約 7000 億円といわれている。このうち産業用ロボットが９割を占め、その６割を日本が占めるとされている。2025 年には、生活分野や、医療公共分野へのロボットの利用進展が加速され、ロボット市場は８兆円規模になるものと推測されている。ロボット関連の特許や基盤技術も我が国が世界をリードしている。次年度の国の重点領域として、次世代ロボットが上げられており、介護用ロボットやリハビリ支援ロボットなどに重点が置かれるものとみられている。

Fig1. Image-guided Surgical Robotics made in Japan

このように、我が国におけるロボット市場の拡大に大きな期待が寄せられている中で、手術支援ロボットの製品化や臨床応用は遅々として進んでいないのが実情である。日本学術振興会の未来開拓事業（平成 11 年-15 年度）で完成した手術支援ロボットのプロトタイプ(Fig.1)は、遠隔手術が可能なマスタースレーブ型マニピュレータ方式で、従来にないナビゲーションシステムを搭載し、画像誘導下により安全で確実な手術が可能となった。しかし、未来医療の中心的な役割を果たす事が期待される手術支援ロボットは、今後の製品化過程に向けて、企業、臨床医の臨床試験でのリスクならびに経済的負担が大きなマイナス要因となっている。前述した欧米並の、ロボット手術の位置づけや、迅速な審査制度、診療報酬の課題など、限定的な規制緩和だけで我が国はもっと元気になるのである。

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マイクロサージェリにおけるロボット手術システムの有用性の検討

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The Efficacy of Robotic-assisted Microsurgery :Comparative Study in Rat Model

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Abstract: Background: Robot-assisted surgery is thought to facilitate complex and refined procedures. Objective: To evaluate the benefit of robotic assistance for microsurgery. Methods: 20 intestinal anastomosis on rat alternating with and without robotic assistance. A da Vinci surgical system™ with 3-D visualization was used. Surgeon made anastomosis using 6-0 nylon. Operative time and quality was evaluated. And also, dissection of portal vein (n=2) and femoral arteries (n=4) and vascular end-to end anastomosis was attempted with robotic assistance. Results. Equal quality scores and anastomotic leakage were achieved with both techniques. Results: There were no differences in operative time and preciseness of intestinal anastomosis. Although, learning curve of RS group was improved. We could perform one portal vein anastomosis and two femoral arterial anastomoses successfully. Conclusions: In this study, robotic (da Vinci) assistance improved the learning curve of the surgeon while making microsurgical anastomosis thanks to two functions, namely tremor canceling and motion scaling. These results support further clinical investigation of robotically assisted microsurgery.

Key words: da Vinci, Robotic assisted microsurgery, tremor canceling,

1. 背景

顕微鏡下に微細血管吻合を行うマイクロサージェリは形成外科のみならず肝移植術や遊離空腸による消化管再建術など、一般外科でも応用が幅広い手技であるが、①微細な針糸の取り扱いが難しい、②術者の手指振戦の影響が大きい、③作業空間が狭く集中力を要する、④習得には多くの訓練を要する、などの理由により、特殊手技の域を出ないのが現状である。この問題を解決する目的で Microsurgery を対象とした Master-Slave 型 Robotic System の開発が進んでいる。一方、da Vinci(Intuitive Surgical, USA)は高度な機能を有する市販の Master-Slave 型手術支援ロボットで、我々は通常の鏡視下手術より優れていることを一般的な鏡視下手術のタスクスコアによる検討にて証明した。(Fig1)

da Vinci の内視鏡は最短焦点距離において 10 倍の拡大率があり、鉗子は狭い空間での作業に適している。また、術者の手の動きを縮小して再現する motion scaling 機能や、手指振戦を除去する機能を有しているため、Microsurgery においての有用性が期待できる。これまで冠動脈バイパス術、精管吻合の実験的検討は報告されているが、マイクロ血管吻合の基礎的検討の報告例はない。

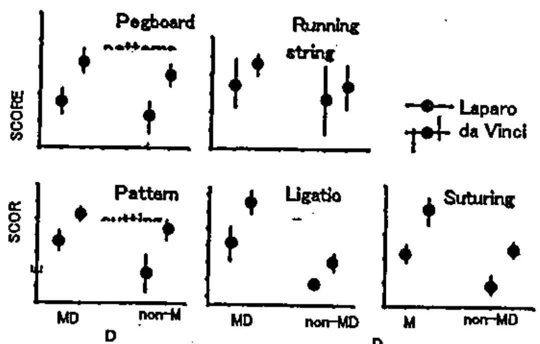

Fig.1 Basic Task Score Results (Conventional Laparoscopic Surgery VS da Vinci)

2. 目的

da Vinci のマイクロサージェリにおける有用性を、通常の顕微鏡下手術と比較検討する。

3. 方法

体重 300g 前後の Wistar 雄性ラットを以下、顕微鏡

下手術群(MS:Microscopic Surgery 群)と da Vinci(RS:Robotic Surgery 群)の2群に分け、以下の検討を行った。da Vinci の鉗子は左右とも、7自由度を有する Microforceps (Fig2) を使用した。

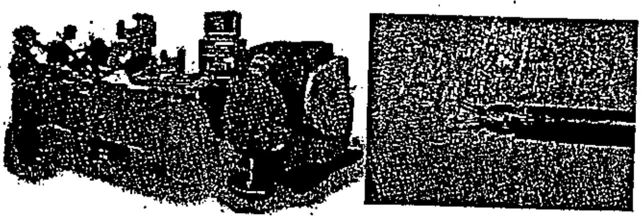

Fig.2 da Vinci System and 7DOF microforceps

①腸管吻合(径3mm前後)による検討：ラットを正中切開にて開腹。大腸を2カ所クリッピング後切離。6-0 ナイロン糸を用い全層一層連続縫合にて端端吻合。吻合部は色素注入により leakage test を行い、縫合の quality、操作時間、全手術時間、エラー発生を比較した。

②血管剥離吻合 (径1mm前後)による検討:ラット門脈(n=2)及びラット大腿動脈(n=4)の剥離及び 10-0 ナイロン糸による端々吻合が可能かどうかを検討した。

4. 結果

①Microsurgery の経験のない術者が実験を行い、縫合 knot 数は、両群とも前後壁合わせて10針、吻合に要した時間は MS 群(n=20):613±291 秒、RS 群(n=20):536±114 秒、と有意差を認めなかった。平均値に有意差はなかったが、MS 群で標準偏差が大きく RS 群では小さかった(Fig3)。エラー(狭窄、leak)は両群とも 2 例(10%)で差はなかった。 Learning curve の比較では MS 群は通常の learning curve を描いているが、RS 群では最初から吻合に要した時間が短く、すぐに plateau に達していた。

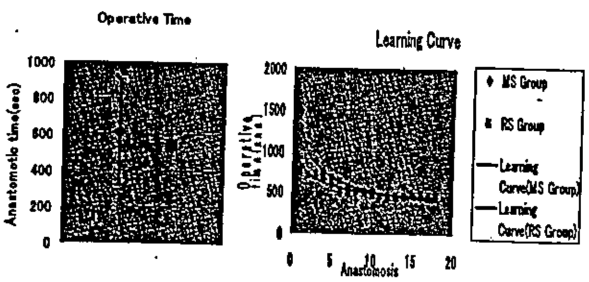

Fig.3 Operative time and Learning curve (Microsurgery VS Robotic surgery)

②門脈吻合(直径 2.0mm)(Fig4) 完遂 1/2(50%) 開存1例 手術時間 21分30秒

大腿動脈(直径 0.8mm) 完遂 2/4(50%) 平均手術時間32分40秒 開存2例

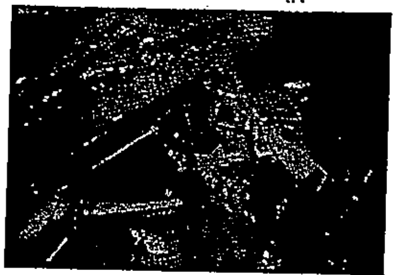

Fig.4 Robotically assisted portal vein anastomosis

■■■■

精密手術におけるRobotic Surgeryの有用性に関する検討がいくつかなされている。Goldbergらはヒトの卵管吻合で[1]、Ruurdaらはブタで本実験と同様の腸管吻合の実験を行っているが、吻合の質はda Vinciは対照群とで有意差はなく、縫合時間はいずれもda Vinciグループの方が長かったと報告している[2]。本実験では、両群の吻合時間や正確さは有意差を認めなかった。Learning Curveと操作の安定性でRS群の方が優れていた。直視視野における顕微鏡下手術との比較のため、視野はほぼ同一、鉗子先端の自由度も同じであるため、両群の差は、振戦除去機能とMotion Scaling機能というソフトウエア的に付加された機能によって生じたものと考えられる。鉗子の操作性に制限を受ける鏡視下手術と比較するとこの差はより大きくなると考えられる。触覚力覚のフィードバックがなく、把持力が強すぎることは弱点の一つに挙げられるが、冠状動脈吻合後の組織学的検討例においても通常手術との差は認められていない[3]。

■■■■

手術支援ロボット da Vinci を用いた Microsurgery は、習得期間の短縮と手技の安定が期待でき、鏡視下手術の適応を拡大させうると考えられた。

■■

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再帰性投影技術を用いた デスクトップ型バーチャル作業環境の研究

Study of virtual desktop working environment using retro-reflective projection technology

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Abstract : We propose a new-type virtual workbench named *X'tal Desk*, which is an integrated system of object-oriented display and retro-reflective projection technology(RPT) on the desk. The system enables the user to handle quite natural 3D objects without occlusion problem or contradiction between convergence and accommodation. We also propose an approach to measure location and orientation of the objects on the workbench by using a couple of cameras and IR light sources.

Key Words: *virtual reality, retro-reflective projection technology, object-oriented display.*

1. はじめに

人間は手先の作業をするとき、しばしば机に向かって行う。一種類の作業に限らず、書類の読み書きであったり、PCの操作であったりと、机に向かって行う作業は多種多様である。これは、机という形状が汎用的であり、様々な作業に適しているからである。

一方で近年、様々なバーチャル作業環境が提案されている。遠隔会議支援システムである *The Office of the Future*[1]は、バーチャル会議室の映像を室内の机や壁に投影することでコミュニケーションを支援する。*TouchDrum*[2]は、両手で行う様々な作業を、実世界で行うのと同様の感覚でユーザにバーチャル体験させることができる。*ImmersaDESK*[3]は、ユーザの正面に大きな一枚のスクリーンを斜めに置いた、机に似た形状のデバイスであり、ユーザにバーチャル空間への没入感を与えることができる。

しかしこれまで、人間の作業に適した環境である机上で、かつ実世界での作業と同じ感覚でバーチャル作業を行える汎用的な環境と呼べるものはなかなか提案されてこなかった。

そこで我々は、本稿において、デスクトップ型の汎用バーチャル作業環境として、*X'tal Desk* と称するディスプレイシステムを考案した (図1)。

X'tal Desk では、再帰性投影技術[4] (*Retro-reflective Projection Technology*、以下RPTと記す) と呼ばれる手法を用いてオブジェクト指向型ディスプレイ[5]を実現する。さらに、デスク面への映像提示などを組み合わせることにより、従来より研究されているバーチャル物体の提示にとどまらない、机という形状を生かした新しい形態の作業環境を提案する。

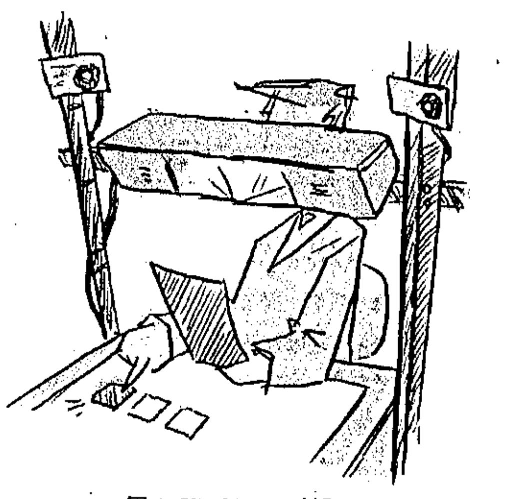

図1: X'tal Desk 外観

2. 背景

2.1 オブジェクト指向型ディスプレイ

オブジェクト指向型ディスプレイは、川上らによって1999年に提案されたディスプレイ方式である[5]。それまで主に使われていたHMDやCABINのような没入型ディスプレイがバーチャル空間そのものを提示することを目的としていたのに対し、オブジェクト指向型ディスプレイは実空間内にバーチャル物体を提示することを主眼に置いている。川上らの手法では、バーチャル物体を提示したい位置の近傍に実物体のスクリーンを配置し、そこにバーチャル物体を表示することでユーザに向けて提示する。また、実物体であるスクリーンの位置にバーチャル物体の投影位置を追従させておく。この状態で、ユーザは実物体のスクリーンを動かすことであたかもバーチャル物体を動かしているかのように操作することができる（図2)。オブジェクト指向型ディスプレイを実現するにはいくつかの問題があるが、川上らはRPTを導入することでそれらを解決した。

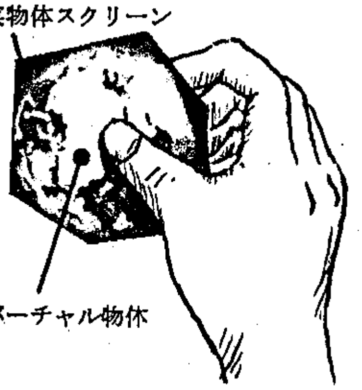

図2: オブジェクト指向型ディスプレイ

2.2 RPT

RPT投影系は、バーチャル物体を投影するためのプロジェクタおよびハーフミラーからなる。それらを図3のように組み合わせ、スクリーンとなる再帰性反射材に向けバーチャル物体を投影する。再帰性反射材は入射光を来た方向へと反射する特性をもつ（再帰性反射特性）ので、投影された映像はハーフミラーを透過してユーザの視点へと戻ることになる。したがって、ユーザに対して再帰性反射スクリーンの位置にバーチャル映像を提示することができる。

RPTの特長として、次のような点が挙げられる。

- 立体形状のスクリーンに対して、歪みのないバーチャル映像を投影・提示できる
- バーチャル物体の提示位置に実物体のスクリーンが存在するため、輻輳や調節の矛盾が抑えられる
- ユーザの視点と光学的に共役な位置から投影した映像は、ユーザの視点にのみ返るため、多視点からの投影や立体視が容易である
- 光が来た方向へ選択的に強い光が返るため、非常に高輝度なバーチャル映像を提示できる

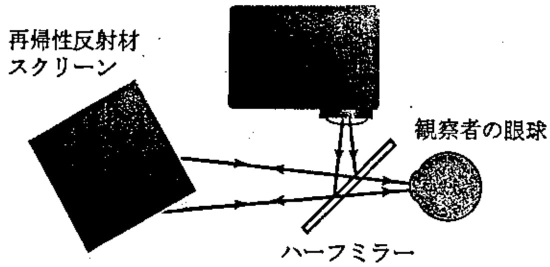

図3: RPT投影系と再帰性反射スクリーン

- 再帰性反射材部分とそうでない部分の輝度差が大きいため、ビデオ撮影した映像上で再帰性反射材部分の切り出しが容易に行える
- 遮蔽問題が生じない

この中で最も大きな特長は、最後に挙げた遮蔽問題が生じない点である。次節ではその点を詳説する。

2.3 遮蔽問題

オブジェクト指向型ディスプレイを構成するとき、最も問題になるのは遮蔽問題である（図4)。遮蔽問題は、実物体がバーチャル物体と重畳したときに、お互いの前後関係に矛盾が生じることであるから、ユーザがバーチャル物体に触れることができるオブジェクト指向型ディスプレイでは特に大きな影響を受ける。人間の視覚は遮蔽の矛盾に非常に敏感なので、リアリスティックなバーチャル映像の提示のために遮蔽問題の解決は必須である。

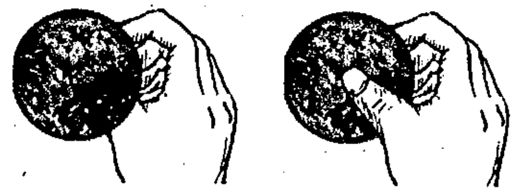

図4: 遮蔽問題 （左）遮蔽矛盾あり（右）遮蔽矛盾なし

RPTは、遮蔽問題を解決することができる映像提示手法の一つである。前節で紹介した通り、RPTでスクリーンに用いられる再帰性反射材は視点方向に強く光を返す。したがって、投影映像の光量を減らしてもユーザに対して明るい像を提示することができる。一方、通常の物体の表面では光が拡散反射してしまうために、光量を減らした投影映像はほとんど観察できない。したがって、RPT投影系を用いれば、バーチャル物体の手前に実物体が存在した場合でも、実物体の表面にはバーチャル物体が提示されないため、遮蔽の矛盾は起こらない。

2.4 再帰性反射材スクリーン領域の取得

RPTを用いたオブジェクト指向型ディスプレイでは、スクリーンとなる再帰性反射材の領域を追従してバーチャル物体を投影しなければならないため、何らかの方法で視点とバーチャル物体の相対位置関係を取得する必要がある。

過去の研究においては、川上らが再帰性反射材のスクリーン位置の取得に Polhemus 社の磁気センサを使用した [5]。また、多田らは再帰性反射材の特性である高輝度反射を用いてスクリーン位置の切り出しを行っている [6]。

3. X'tal Desk

3.1 X'tal Desk とは

我々は、前章で述べた RPT の特長を生かした作業環境として、X'tal Desk と称するデスクトップ型バーチャル作業環境を提案する。X'tal Desk は、オブジェクト指向型ディスプレイをデスクトップ型作業環境に取り入れたものであり、次のような機能を提供する。

- 実物体のスクリーンにバーチャル物体を投影し、ユーザに提示できる
- 手やペンなどの実物体の位置を取得できる
- デスク面にも映像を表示できる

3.2 X'tal Desk の構成

X'tal Desk は、着座したユーザの前方に水平なデスク面を持つ机型である（図 5）。デスク面はリアプロジェクション用のスクリーンとなっており、デスク面下部のプロジェクタによって映像を投影することができる。

一方、デスクには、着座したユーザが覗き込みやすい位置に RPT 投影系が固定されている。RPT 投影系はデスク面全体を見渡せるような向きにあらかじめ調節しておく。ユーザは RPT 投影系の光学系を通してデスク面を観察する。

ユーザの視点近傍には、複数台の赤外ビデオカメラが設置され、デスク面上を撮影する。取得した映像は画像処理用の PC に送られ、PC はそれらの情報を用いてデスク面の映像および RPT 投影系が提示する映像を生成する。また、PC は赤外ビデオカメラが映像を取得する際に必要な赤外光を与える赤外光源（ビデオカメラ付近およびデスク面下部のプロジェクタ付近に設置）も制御する。

次節以降では、これらの構成と機能について詳説する。

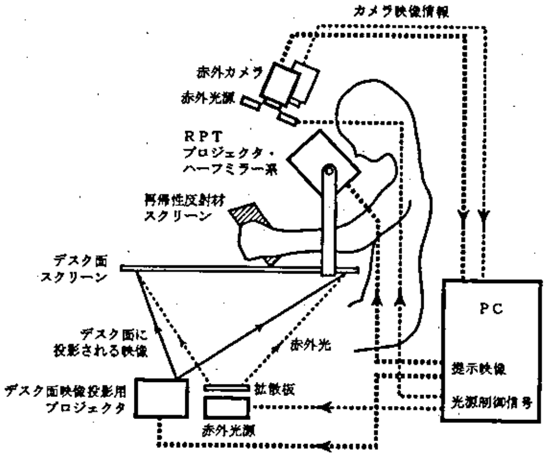

図 5: X'tal Desk システム概要

3.3 デスク面への映像提示

RPT 投影系により、再帰性反射材スクリーン上にはバーチャル物体を提示することができるが、このままでは再帰性反射材以外の部分、とくにデスク面に映像を提示することはできない。しかし、過去にも *metaDESK*[7] などの研究例があるように、デスクトップ型の作業環境ではデスク面も映像情報を提示できる重要な空間であると考えられる。そこで我々は、X'tal Desk のデスク面に映像を提示する手法についても検討した。

以下に候補となった手法を挙げる。

1. デスク面に低輝度の再帰性反射材を使用し、バーチャル物体提示用の RPT 投影系で映像を提示する
2. デスク面にプラズマディスプレイや液晶ディスプレイを用いる
3. デスク面をスクリーンとし、プロジェクタで映像を投影する

手法 1 では、デスク面にバーチャル物体提示用の再帰性反射スクリーンとは反射輝度の異なる再帰性反射材を使用し、バーチャル物体提示スクリーン・デスク面映像提示スクリーン・実物体（ユーザの手など）の三領域を反射輝度の違いで識別する。しかし、デスク面に提示する映像の視認性を上げるためにはそれなりの輝度を確保しなければならず、結果として各スクリーン領域の切り出し性能が著しく低下するために、この手法は現実的でない。

さらに手法 2 と手法 3 を比較した結果、後述するデスク面上の実物体領域の切り出しが容易である手法 3 が優れていると判断し、デスク面に対してリアプロジェクションによる映像投影を行うことにした。

3.4 再帰性反射材スクリーン領域の切り出し

RPT を用いると、再帰性反射材部分とそうでない部分の切り分けが非常に容易になることは前に触れた。

X'tal Desk は、バーチャル物体を提示するスクリーン部分がすでに再帰性反射材である。したがって、レンズ近傍に照明を設置したビデオカメラでデスク面を撮影すれば、撮影された映像上でバーチャル物体提示用スクリーン領域が非常に明るくなるため、複雑な画像処理なしでスクリーンの切り出しを行うことができる。

ビデオカメラを設置する位置については次節で検討する。

3.5 再帰性反射材スクリーン上の実物体領域の切り出し

前節では、再帰性反射材スクリーンそのものの位置を切り出す手法について述べたが、再帰性反射材スクリーン上に手など実物体の遮蔽物が存在する場合、遮蔽物の領域も同様の原理で切り出すことができる。

多田らは、再帰性反射材スクリーン位置の取得に、視点と共役な点に設置したビデオカメラの映像を使用した [6]。スクリーンの形状が既知であれば、一視点の映像からスクリーンの位置姿勢を得ることが可能である。また、多田らは再帰性反射材上の指先位置の検出も行っている。