1 Introduction
One of the main issues in current tele-operated medical robotics is the loss of tactile information and the change of senso-motoric coordination. The desire for obtaining a natural and intuitive way of human–machine interaction and for multi-modal sensory feedback to users has resulted in the design of haptic interfaces. At present, they are still confined mainly to research and development facilities, although there are some general purpose commercial devices. These interfaces are generally used in two contexts: tele-manipulation and computer simulation. Diverse control architectures and models have been proposed in order to achieve the haptic perception.
2 Methods
The control architectures for haptics can be classified based on the types of control variables, low level algorithms, and coordinate systems used. Some architectures and models differ by means of special treatments: gravity compensation, friction, time delay, virtual coupling and fixtures, human model and human performance. In order to present further analysis of the classification, we performed simulations using a system of 1-DOF. The systems are identical at both master and slave sides, without the need of mapping either systems or scale effects. The structures were analysed based on the classification of control variables.
3 Results
Position/position architectures neglect internal and external forces. In contact situation with stiffer bodies on the slave side high-gain motion may result in damage of manipulator and body, instability and actuator saturation. Force/position architectures require the transformation of variables in order to compare variables and to generate the error signal. The force measurement on the slave side is of special importance in case of contact of the device with the environment. The position measurement is essential for geometric precision. Force/force architectures tend to instability when there is no contact on one of the sides, however working better in contact situation.
4 Conclusion
The control in haptics involves the coordination between master and slave devices. In the medical field, the procedure in question defines the important variables and constraints to be treated by the system thereby defining the control architecture to be used. In some cases, it could be necessary to use hybrid systems, for example when it is necessary to have force and position measurement of the intervention site. Moreover, risk analysis and needs for redundant sensors and control systems have to be taken into consideration.
Acknowledgment This work has been partially supported by Foundation CAPES/MEC, Brazil.

Simultaneous measurement of position and orientation for interventional MRI devices

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Keywords MRI guidance · Minimally invasive surgery · Invasive device tracking
1 Introduction
In this paper, we suggested the extended active tracking method based on active tracking principal [1] for minimally invasive surgery with MRI guidance and surgical navigation system. Our method can measure both the position and orientation of the small receiver coil with three series inductances (Fig. 1).
2 Methods
In this study, 0.3-T open MR scanner (AirisII, Hitachi Medical Co., Chiba, Japan) was used. In order to evaluate the basic performance

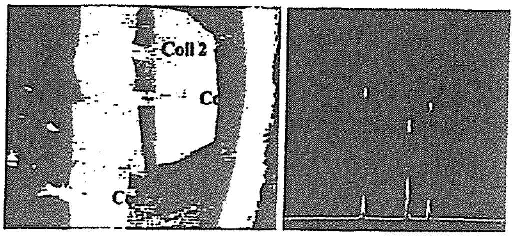

Fig. 1 *Left Panel* The tracking coil assembly with three series inductances (Coil 1, Coil 2, Coil3). It can measure both the position and orientation of itself. *Right Panel* The image of the tracking coil assembly and projection data. The peaks of projection data indicate the position of each inductance

of the proposed method, we conducted following three experiments. The first experiment was the flip angle optimization for the reduction of background noise by the proton around each inductance. The second experiment was reproducibility evaluation. The 20 times of measurements were repeated while placing the tracking coil assembly at the same. The third experiment was measurement accuracy evaluation. The difference of measured value between the proposed method and an optical tracking system was compared.
3 Results and conclusion
In the flip angle optimization, the NMR signal peaks, which indicated the position of each inductance, were not clearly at 60° flip angle. On the other hand, all peaks were clearly at 7° flip angle. In the reproducibility evaluation, standard deviation of measurement positions was less than 0.4 mm. In the accuracy evaluation, the difference between the proposed method and the optical tracking device was 0.43 mm (RMS). It was concluded that this method could be used instead of an optical tracking method.
Acknowledgment This study was partially supported by "Research on medical devices for analyzing, supporting and substituting the function of human body" funded by Ministry of Health, Labour and Welfare.
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Automatic segmentation of hip bone surface in ultrasound images using an active contour

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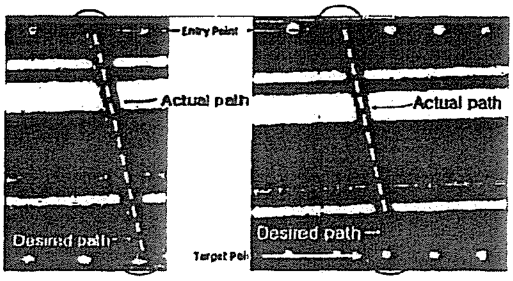
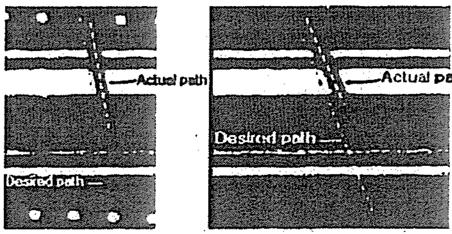
Keywords Ultrasounds · Segmentation · Active contours · Orthopaedic surgery
1 Introduction
We propose an automatic bone surface detection from ultrasound images. Our model is based on an active contour with a force that pushes the contour upward and a regional energy term. Results are then used as an input for a feature based registration in the context of computer assisted hip surgery applications.
2 Methods
Active contours [1] are usually defined with an internal energy that imposes the regularity of the curve and an external energy that draws the contour towards the significant features. The segmentation process is then achieved by minimization of the sum of these two energies. To avoid the model finding a local minimum solution, Cohen [2] proposes an additional force during the optimisation, pushing the contour along its normal direction. Given that in ultrasound images, a dark shadow can be found below the bone surface, we incorporate such a force in the vertical direction to push the contour upward from the shadow area to the bone surface.



(a) Result #1 (b) Result #2

Fig. 1 Experimental result: the path of drilling by human



(a) Result #1 (b) Result #2

Fig. 2 Experimental result: the path of drilling by SPINEBOT

automatic mode. But, significant deviation error was observed in the experiments. The deviation error comes mostly from one specific inaccurate sensory system component, OTS. Replacement by a more accurate OTS along with employment of better calibration methods for the system components would reduce the deviation error and lead to successful implementation of the robotic system for spinal fusion.

Design of modular master-slave surgical robotic system for integrating independently developed forceps manipulator

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Keywords Master-slave system · Medical robot · Modular system · Forceps manipulator · Laparoscopic surgery

1 Introduction

This paper describes to develop a real-time modular slave manipulator system, which can integrate various independently developed forceps manipulator, and the results of experiments to evaluate the utility and performance of this slave manipulator system as one application of modular master-slave system.

2 Methods

We proposed a new system configuration with following two major functional systems to realize develop a real-time modular slave manipulator system, which can integrate various independently developed forceps robot: Two kinds of control systems, forceps manipulator control system and arm robot control system, to avoid performance changes caused by the introduction of forceps manipulator with individual control interval and Modular system with asynchronous capabilities of safe and quick interchange of an integrated forceps.

3 Results

Master-slave operation was performed while changing the three kinds of forceps manipulators several times [1–3]. Safe and quick removal of integrated forceps manipulators from the slave manipulator system during a surgical operation was realized and the probability of feasible interchange of forceps was indicated (Fig. 1). We could realize real-time modular slave manipulator system, which can integrate independently developed functional forceps.

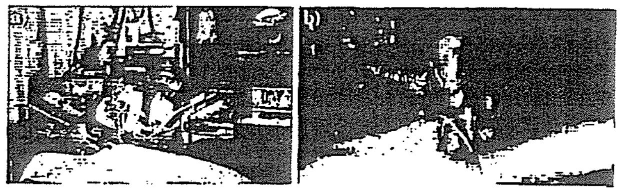

Fig. 1 In vivo experiment: a Overview of master-slave operation b Ablation of bile-duct using electric scalpel forceps

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Evaluation experiments on wide FOV wedge prism endoscope

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Keywords Endoscopic surgery · Minimally invasive surgery · Wide field of view · Wedge prism · Medical robot

1 Introduction

We have developed the endoscope system that can be used to observe a wide field of view without moving or bending the whole endoscope system [1, 2]. By attaching two wedge prisms at the distal tip of general rigid endoscope and rotating them respectively, the direction of view can be changed. Accordingly it is possible to observe a wide field of view with the endoscope being fixed, and it does not damage body tissues or internal organs. In this study, a couple of evaluation experiments have been conducted to confirm that this endoscope system would be acceptably used in clinical use.

2 Methods

Firstly, the maximum moving angle of local field of view and the global field of view was measured so that we could check that this endoscope system is able to observe sufficiently wide field of view. Secondly, we conducted image quality evaluation about chromatic aberration, resolution, and distortion. Finally, we conducted a performance evaluation about moving field of view because it is important to observe the area which the surgeon needs to see.

3 Results and conclusion

As a result, 93° FOV was obtained by using 55° FOV rigid endoscope, and the direction of view can be changed from 0 to 19°. In the image quality evaluation, there is no significant problem now, but to improve image quality, the distortion is desired to be corrected.

In the performance evaluation, field of view is moved in allowable range, but return-to-the-origin-error may as well be corrected because it might affect to degrade the accuracy of the movement.

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A Novel Robotic Laser Ablation System for Precision Neurosurgery with Intraoperative 5-ALA-Induced PpIX Fluorescence Detection

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Abstract. We developed a combined system of tumor detection by 5-ALA-induced PpIX fluorescence and precise ablation by micro laser for the first time, with an automatic focusing and robotic scanning mechanism for the brain surface. 5-ALA accumulates on tumors to be metabolized to become PpIX that is a fluorescent. Intra-operative detection of 5-ALA induced PpIX fluorescence provides useful information for tumor detection. The wavelength of the micro laser is 2.8 μm close to the absorption band of water. This laser is effective only on the surface of brain tissue, enabling precise ablation at the boundary between tumor and normal tissue identified by intra-operative 5-ALA induced fluorescence. Combination tests of the fluorescence measurement and the laser ablation were performed, and it was possible to extract the area with fluorescence appropriately from the measurement data, and the micro laser with automatically scanning selectively ablated the extracted area.

1 Introduction

In current neurosurgical practice, surgeons can remove most of a tumor with an accuracy of a few millimeters by using a combination of conventional surgical instruments, such as an electric cautery, and a computer-aided navigation system based on diagnostic images, such as MR and CT images. Residual tumor, especially if the malignant tumor like glioma, may impair the prognosis of the patients and it is necessary to remove as much of the tumor as possible while keeping the normal tissue

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intact. However, it is difficult to know the exact boundary between tumor and normal tissue, and excessive ablation of the normal brain tissue will damage its function.

In craniotomy procedure, deformation of the brain tissue, called "brain shift", occurs due to cerebrospinal fluid leakage and surgical interventions. In some cases, brain shift reaches to several tens of millimeters and continuously increases during the procedure [1]. This requires navigation based on intraoperative MR images. This navigation, however, contains a few millimeters of errors at a maximum caused by a registration of preoperative diagnosis images [1] and intraoperatiove images and an accuracy of the position tracking using such as an optical marker. Furthermore, there is a tradeoff between high frequency of image acquisition for more accurate navigation and not time-consuming imaging.

Similarly, the accuracy of conventional surgical procedures is a few millimeters for removal of residual tumors. Therefore, we desired to achieve a more precise operation with an accuracy of sub-millimeters. To that end, each of a measurement and removal of residual tumors has to realize this accuracy.

To solve these problems, we have proposed a novel approach to therapy using 5-aminolevulinic acid (5-ALA) [2][3] and a micro-laser ablation system [4], with the boundary between the tumor and the normal tissue distinguished by the 5-ALA-induced protoporphyrin IX (PpIX) fluorescence in the tumor and with accurate ablation of the tumor with the micro laser. 5-ALA, which is orally administrated to a patient, accumulates on tumors to be metabolized to become PpIX that is a fluorescent substance [5]. The wavelength of the micro laser is 2.8 μm. Light with this wavelength is mostly absorbed by water, and therefore this laser is effective only on the surface of brain tissue, enabling precise ablation at the boundary between tumor and normal tissue [4].

In this paper, we developed a combined system of tumor detection using 5-ALA and precise ablation by micro laser, with an automatic focusing (AF) and robotic scanning mechanism for the brain surface. This system is designed for possible localized pinpoint detection of the tumor, then ablating the fluorescent area with stepping driven precise position control in the whole system. This is first attempt to integrate intraoperative fluorescence detection and high precision laser ablation system. In addition, each of the measurement and ablation is performed under the robotic position controlling.

2 Materials and Methods

In this chapter, the tumor detection using 5-ALA-induced PpIX fluorescence, the micro laser module, the automatic focusing and robotic scanning system, and the whole system integration are described. Finally we proposed the experimental procedure for combining these surgical processes.

2.1 Intraoperative Detection System for Brain Tumor Using 5-ALA

Fluorescence of PpIX is fully observed a few hours after orally administrated 5-ALA. Irradiating near-ultraviolet light of around 400 nm, PpIX emits the fluorescence of the wavelength of 635 nm at peak intensity from the brain tissue.

Applying a highly sensitive camera is one of the reasonable ways for intraoperative detection of PpIX fluorescence. Although it is possible to acquire a wide-area 2-dimensional data at one time, obtained data contains only light intensity and simple color information. As PpIX fluorescence is so much weaker than the excitation light and a guide laser of the AF system, it requires the optical narrow-band-pass filter to cut off the other light sources. Nevertheless, it is difficult to separate the fluorescent component from the intensity and the color information of the image signal. Therefore, we chose the use of a spectral photometer, easily extracting the peak intensity of the fluorescence. The spectral data contains important information about tumors; for example, a spectral shape and a peak wavelength possibly vary with a density of tumor cells, a class of tumors, and other conditions of tissues. In the future task, we consider acquisitions of the functional information of tumors by spectral analysis.

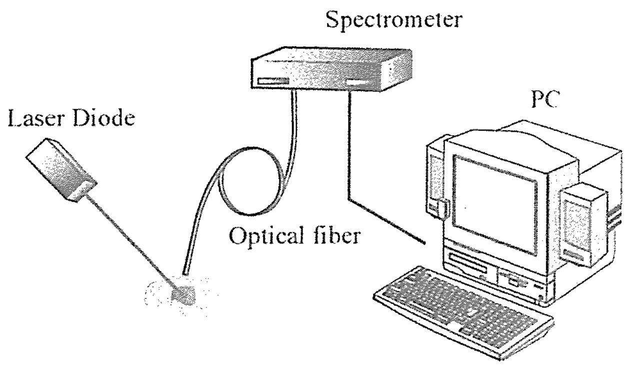

Fig. 1. Tumor detection system using 5-ALA-induces PpIX fluorescence

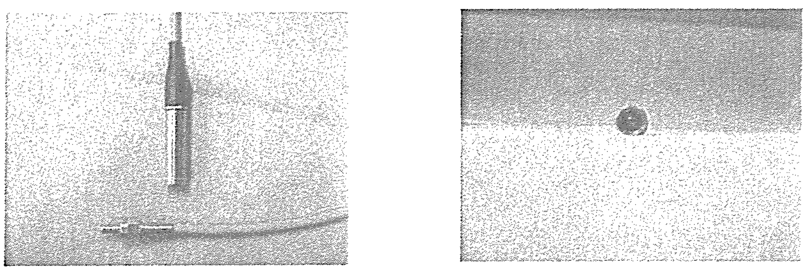

Fig. 2. Fluorescence detection probe

PpIX fluorescence was collected by a detection probe and guided into a spectrophotometer through an optical single-mode fiber, then performed spectral analysis (Fig. 1). The detector has a diameter of 8 mm, using aspheric lenses to correct aberrations. The detection resolution is set to 0.6 mm, considering a tradeoff between not decreasing of the acquired light intensity in proportion to the square of the resolution diameter and improving the accuracy of the measurement (Fig.2). A band-pass filter, which transmits over 60 % at 635 nm and up to 5 % at 670 nm, was fixed on the tip of the detector, cutting off the excitation light and the guide laser (peak at 670 nm) of the AF system. The working distance of the detector is 16 mm to a tolerance of plus or minus 0.5 mm.

2.2 Micro Ablation Laser Module

For ablation of tumor tissues, we used a mid-infrared continuous-wave laser with a wavelength of 2.8 μm, being output by a microchip solid-state laser on the tip of a laser probe [4]. The pumping light source for the solid-state laser is a near-infrared diode laser with a wavelength of 970 nm, guided through a quartz optical fiber to the laser probe.

As the light wavelength around 3μm has strong absorption feature by water, this laser is effective only on the surface of the living tissue, and it can make a precise ablation with a low output of 0.2 W or less. The laser beam is focused to a diameter of 0.1 to 0.15 mm with a lens, and an ablation groove is formed equivalent to the spot diameter in the soft vital tissue. The working distance of the laser probe is 15 mm ± 1 mm.

2.3 Automatic Focusing and Robotic Scanning System

Both the fluorescence detection probe and the micro laser probe have each working distance, and this requires an AF mechanism, constantly maintaining the distance from the brain surface. In this practice, we used an AF system designed based on the three-dimensional measurement system (Mitaka Ko-ki Co., Ltd.) (Fig. 3). In this system, position measurement was performed using a confocal optical mechanism and the guide laser was picked up with a split photodiode, enabling a focusing with an accuracy of micrometers. The wavelength of the guide laser is 670 nm. This system was coupled with 2-axial automatic stepping drive stage and can make a robotic scanning on the surface of the brain.

Fig. 3. Automatic focusing and robotic scanning system

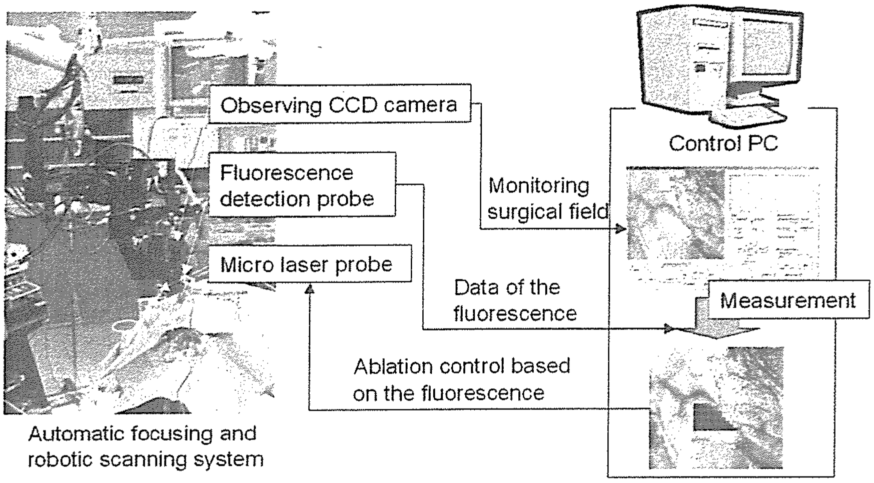

Fig. 4. System configuration

2.4 System Integration

Fig. 4 shows the system configuration in this paper. The fluorescence detection probe and the micro laser probe were attached to the AF system. The data from the spectral photometer was stored into a personal computer (PC). Switching of the micro laser and scanning with the stepping drive were both controlled by the PC. We can observe surgical field view by a CCD camera in the AF system. This image was used to control electric motors to position the fluorescence measurement system and the laser ablation system.

2.5 Experimental Procedure

Measurement of Fluorescence Signal

Measurement area was defined on a CCD camera view of the AF system and sectioned in a grid pattern. Measurement was performed on each grip point with raster

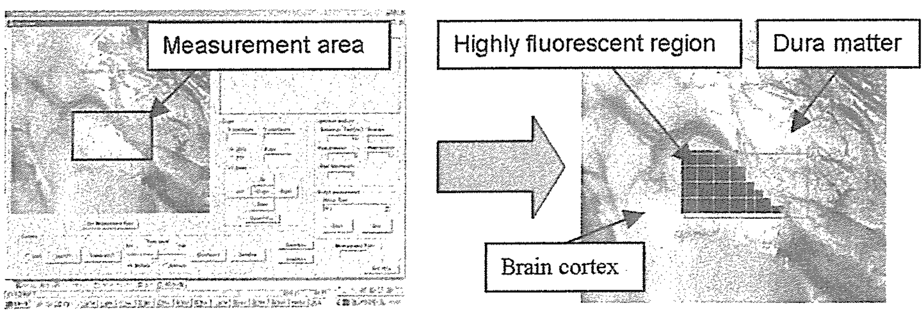

Fig. 5. An example of the measurement procedure of the fluorescence on a porcine brain

scanning. A point in the measurement area was regarded to have same fluorescent property with nearest grid point. A grid interval was determined to 0.4 mm, considering that the grid square was included in the circle of the measurement resolution of 0.6 mm. As a measurement required more than a few hundred of milliseconds, it took several tens of seconds or more to measure a few millimeters square. Fig. 5 shows an example of the fluorescence measurement procedure.

Ablation of the Target Area

A threshold was set for the intensity level of measured fluorescence. In this paper, a surgeon or an experimenter determined the threshold, viewing the measurement area on the CCD camera image. Then scanning was started, and the micro laser was automatically irradiated on the region over the threshold.

3 Results

Combination tests of the tumor detection system and the micro ablation laser module were performed for a biomedical simulant material (phantom) and a porcine brain.

3.1 Phantom Experiment

The phantom was composed of agar plate containing Intralipid-10% that is intraenous lipid emulsion and used for scattering medium [6]. The concentration of Intralipid-10% was adjusted so that the scattering coefficient became 3 cm^{-1}, which is similar to that of Glioma [6][7]. A half part of the phantom contained PpIX to emit fluorescence and the other half part did not contain PpIX.

Fig. 6(a) shows one of the results of experiments. Black rectangular area stands for the scanned area by the system. The system could identify the boundary between the area with fluorescence and without fluorescence, and could precisely ablate the fluorescent area with automatically scanning.

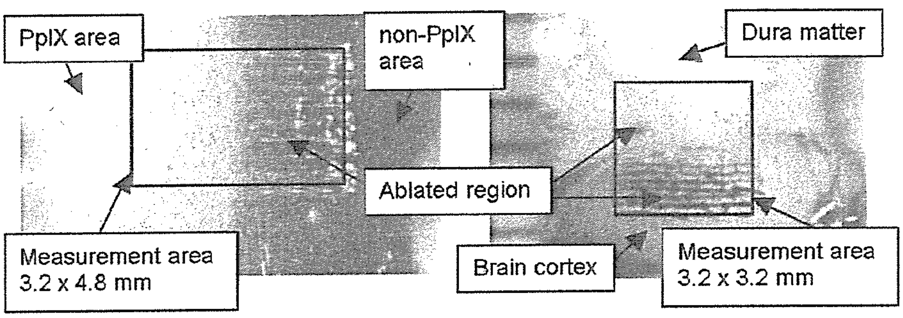

Fig. 6. Result of the combination tests of the tumor detection system and the micro ablation laser module

3.2 Porcine Brain Experiment

The target was the surface of a porcine brain exposed by craniotomy under anesthesia. Before the experiment, 5-ALA was administrated in sufficient quantities to accumulate on a normal brain tissue and metabolize to become PpIX. A half of the measurement area was covered with dura matter, where the fluorescence was not observed, and the other half was exposing brain cortex.

Fig. 6(b) shows one of the results of experiments. Black rectangular area stands for the scanned area by the system. The dura matter covering the porcine brain could not completely block the fluorescence. We could identify weak signal of fluorescence from some part of the dura matter. As shown in Fig. 6(b), ablation laser was irradiated to such area on the covered region. We could successfully identify and ablate the fluorescent area of the porcine brain based on the fluorescence data. The AF system functioned properly even for porcine brain and was effective to stabilize both of the conditions of the measurement and the laser ablation.

4 Discussion and Conclusions

We developed a combined system of tumor detection by 5-ALA-induced PpIX fluorescence and precise ablation by micro laser for the first time, with an automatic focusing and robotic scanning mechanism for the brain surface. In this system, ablation was performed based on the fluorescent information under the robotic position controlling.

Combination tests of the fluorescence measurement and the laser ablation were performed for a biomedical simulant material (phantom) and a porcine brain. Measurement areas of the phantom and the porcine brain were both separated into fluorescent part and non-fluorescent part. In each test, it was possible to extract the area with fluorescence appropriately from the measurement data, and the extracted area was selectively ablated by the micro laser with automatically scanning.

In this practice, the experimental targets were clearly separated into the area with fluorescence and without fluorescence. In clinical cases, the boundaries between tumors and normal tissues are often unclear, and tumors invade normal tissues. Therefore, thresholding of a fluorescence data and an extraction of the area for ablation will have problems, and are considered making some automation process. Solutions for these problems are desired in the future work. To automatically discriminate the tumor region by fluorescence data, a multiple classification analysis based on another spectral features not only peak intensity of the fluorescence will be investigated.

Acknowledgments

We wish to thank many people and groups who have contributed to this effort. Research on medical devices for analyzing, supporting and substituting the function of human body funded by Ministry of Health, Labour and Welfare.

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ロボット外科（精密手術）

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要旨　術中診断技術の発達により、診断即治療のリアルタイム性を追求する診断と治療の融合の時代となった。診断機器と治療機器との一体化により実現される精密手術を効率的に行うためには、術中画像、特にMRIの形態を中心とした画像だけではなく、種々のイメージングを活用した高度な統合医療情報とその有効な活用が重要である。直前の術中画像をリアルタイムにアップデートするナビゲーション技術により、術中のbrain shift（手術操作による脳の変形・移動）を回避し、手術操作を正確にかつ安全に支援することで、機能領域の悪性腫瘍をぎりぎりの切除にまで肉薄できるようになってきた。精密手術は、狭い開口部から狭い空間での作業領域の有効利用をいかに実現するかと言う観点から、必然的に編み出された微細操作技術である。これに必要な治療操作や器具などが、必然的に発達したわけである。狭い治療空間の状況認識が重要で、見えなければどんな治療も行うことができず、またどんな手技・器具が必要かもわからないのは、自明なことである。これを実現する手段として、内視鏡が発達し、内視鏡と一体化した治療器具が、次世代の微細操作マニピュレータとしてのrobot手術システムへとつながったわけである。しかし、いくら微細マニピュレータといえども人間の手の延長上にあることはいうまでもない。さらなる新しい手は、人間の手の能力を超えた治療システムである。人間の手を超える新しい手としては、CAD (computer aided design) -CAM (Computer aided manipulation) surgeryである。それは、手術の工程解析に基づく各手術stageとしてのcompartment 管理と可視化情報と非可視化情報を統合した新しい目に基づく治療である。

Robotic surgery (Precision surgery)

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Abstract Computer-aided surgery commenced in the late 1980s when computer was clinically used for diagnosis and surgical planning. Since then the computer has been used in surgical navigation systems. At the beginning of 1990s a robotic surgery started, in which an intelligent device or a robot was used as surgeon's new hands. The key to achieve minimally invasive operation in neurosurgery will be active use of manipulation (robotic technology) . However it is nonsense to let the robot carry out whatever the man's hands can do. What is important is that the robot performs procedures which only the robot can do. As intraoperative diagnostic imaging devices were improved open MRI devices were installed in operating rooms and intraoperative diagnostic imaging became nothing special. Real-time diagnosis and navigation have already been demanded to be performed intraoperatively. Based on intraoperatively acquired information surgical procedures are precisely determined using computer-aided design (CAD) system. Then according to the procedures surgical devices are controlled accurately using computer-aided manipulation (CAM) system. Therefore, an immediate treatment after diagnosis became possible.

●Key words : precision surgery, master-slave manipulator, CAD-CAM, LASER ablation, intelligent operating theater

Ⅰはじめに

コンピュータ外科は、1980年代後半からコンピュータ統合による診断・手術プランニングに臨床応用することから始まり、手術ナビゲーションシステムへと発展してきた。さらに90年代初頭より、外科医の新しい手であるインテリジェントデバイスとしてのロボット手術が始まった。また、外科医の新しい目として、術中にultrasonogram・X-ray computed tomography (CT)・Magnetic resonance imaging (MRI) の活用が試みられるようになった。1995年ころよりオープンMRIも手術室に設置され、術中に手術操作を加えた状況がほぼreal-timeに評価することができる術中画像診断の時代となった。術中医療情報可視化技術・低侵襲手術が融合した診断即治療の時代が到来し、精密手術（ロボティックサージェリー）が治療の担い手として登場したのである。

Ⅱ外科医の新しい目

外科医の新しい目とは、見えない物を可視化する技術に他ならない。医療のあらゆる局面を「可視化」することによって、患者にとっても医療スタッフにとっても状況が分かりやすくなり、安全・確実・迅速な医療サービスを保証できるようになる。手術室では、術野である現実空間に仮想空間を投影する強調現実技術が、主として使われている。

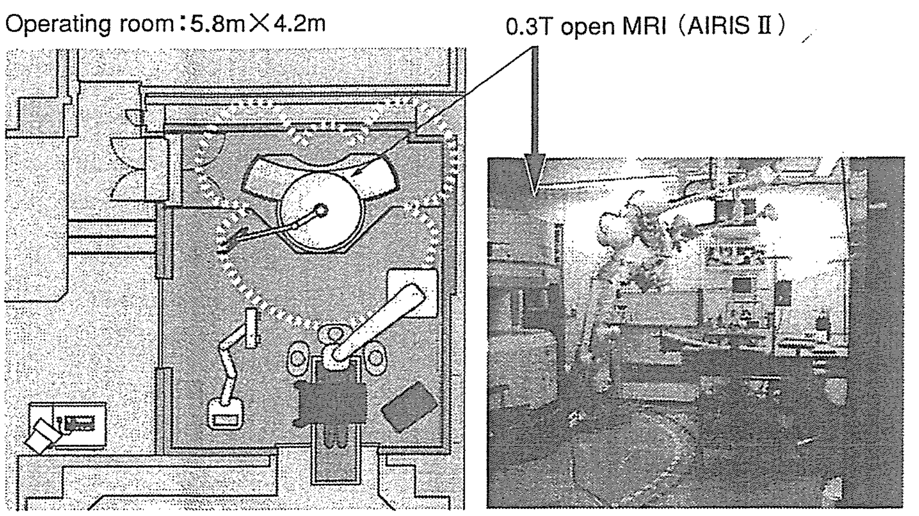
代表的なものは、手術ナビゲーションである。CT・MRIなどの画像を3次元地図として用い、手術中に執刀医が指示した場所がこの地図上のどこにあたるかを提示する手術ナビゲーションシステムは、コンピュータのモニターにMRIなどの断層画像を表示し、現在手術操作を行っている位置をリアルタイムで計測してその画像上にカラーグラフィックスで表示する。術者は操作部位と周囲の3次元的構造との関係を常

時把握できるので、手術の安全性・有効性が向上し、手術時間も短縮できる。

手術室内に設置したオープンMRI AIRIS Ⅱ（日立メディコ製）は、垂直磁場方式永久磁石で、静磁場強度0.3テセラ（T）（共鳴周波数:12.7MHz）のハンバーガー型で開口部が43cmである。漏洩磁場（5ガウスライン）は狭く、中心より左右2.0m、前2.2m、後1.8m、上2.5mの範囲である。冷却システムが不要なため、低ランニングコスト（1万円／月）であるという利点もある。5ガウスラインが狭いということは、狭い手術室内でも十分に通常の手術器具を使えるという別の利点もある。非磁性体で構成された特殊な窒素ガス駆動顕微鏡、麻酔器・モニター（20ガウスまで対応）、手術照明や手術器具も必要である。MRI対応手術用ベッドは、本体および粗動での移動が容易で、かつ撮像位置を調整するためにX－Y平面移動が微調節できる。手術内容に応じた手術用コイルを開発し、診断用コイルと遜色ない画質と手術操作性を両立している。手術室は、5.8m×4.2mの狭い空間ではあるが、5ガウスラインが狭く、手術用器具の制限も少ないため実用的で、一般の手術室よりも広い作業空間と少ない動線を実現した高密度実装型手術室でもある。オープンMRIで術中撮影を行い、手術操作による脳の変形や腫瘍の状況を確認する。次に術中リアルタイムアップデートナビゲーションのために画像転送を行い、手術を継続する。これらの行程を繰り返しながらオープンMRI下での手術を終了するわけである（Fig.1）。

オープンMRIからの術中画像データは、LAN（local area network）を介して、DICOM規格でナビゲーションシステムに瞬時に転送できる。この最新画像で、ナビゲーション画像データをアップデートすることにより、術前画像データを基にした従来のナビゲーションの欠点である術中構造物の手術操作によるbrain shiftなどの諸問題を確実に回避することが可能となった。これにより、悪性腫瘍などの切除率を飛躍的に高めることが可能となった。覚醒下手術や脳波、誘発電位などの各種生理学的モニタリングも一般の手術室となんら遜色なく行っている。脳腫瘍そのものが人によって異なり、不規則な形状や侵潤するという特性を持っている。個人によっても脳の機能領域には差があり、脳外科手術で腫瘍を摘出しすぎると、運動麻痺や言語障害などを引き起こす危険性がある。術後もできるだけ機能を温存し、腫瘍の摘出率を最大にすることが求められている。少しの運動障害が出ても、生きることを優先させるのではなく、日常生活を送ることを前提に治療の質を向上させることで、安心、安全な手術を実現することが、医療現場におけるインテリジェント手術室構築の目的である。特に、手術情報の共有は、手術スタッフ間の迅速な意志疎通を可能にした。また、術中MR画像で患部周辺の状況を確実に把握できるという利点は比べ物にならないほど大きい。

Fig.1 Intelligent operating theater



例えば悪性脳腫瘍においては、術中MR画像で残存腫瘍を確認することにより、安全かつ確実に90～95%の切除率が達成できる。診断と治療の融合による精密治療の実現により、悪性脳腫瘍の切除率を平均93%まで向上させ、全摘出率を約40%（全日本脳腫瘍統計では8%）まで高めた。この疾患では切除率が手術成績を決める主要な要因であり、手術しない場合を含め切除率75%以下では5年生存率が14.8～10.8%であるが、切除率95%以上だと5年生存率22.5%、全摘出できると40.9%である。しかし腫瘍切除率を向上させることだけを目指したのでは、運動領野・言語領野などの重要な機能部位を傷害して重篤な機能障害を生じる恐れがある。このため、術中MR画像やナビゲーションなしで過不足のない高い切除率を安全に達成することは非常に困難である[1)]（Fig.2）。

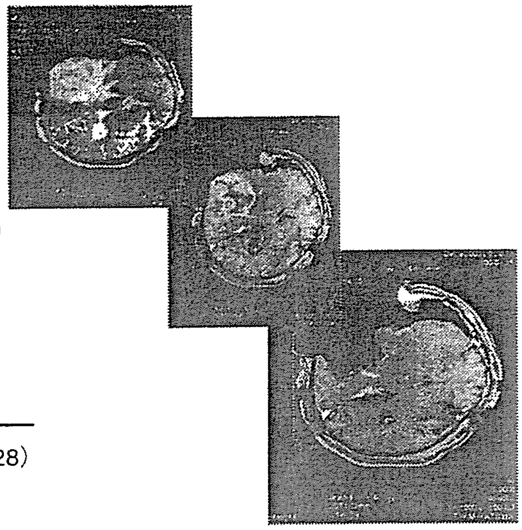
Fig.2 Neursourgical cases & intraopertive MRI

Indication of open MRI

To detect invisible residual mass and confirm hemostasis

- Glioma (293)
  - —eloquent area
- Parasellar tumor (40)
  - —pit. (32), craph. (8)
  - ≫transnasal approach
- Cavernous angioma (27)
- AVM (8)
- Meningioma (6)
- hydrocephalus (3)
- others (33＋(1))

- Navigation (324) DWI (28)
- Awake surgery (62)
- 5-ALA (154)



Total：410cases (2000.3.13－2006.6.26)

Ⅲ外科医の新しい手としての現在のロボット手術用デバイス

現時点では、ロボット手術は、二通りに峻別される。一般にロボットと思われているマニピュレータ：da VinciTM (Intuitive Surgical, Inc., Sunnyvale, CA, USA)、ZeusTM (Computer Motion, Inc., Goleta, CA, USA)、NeuRobotTM (Hitachi, Ltd., Tokyo, Japan)[2,3)] と整形外科で使用されているRobodocTM (Integrated Surgical Systems, Inc., Davis, CA, USA ）や放射線治療ロボット：Cyber knifeTM (Acculay Inc., Sunnyvale, CA. USA) と Gamma knifeTM Model C auto-positioning system (Elekta AB, Stockholm, Sweden)、Laser ablation system (開発中)[4)] に代表されるコンピュータでデザインされたプランニングを基に、そのプランを正確に実行するために、対象と操作系の相互の位置情報を正確に把握しながら治療・ablationを行う手術システムである。前者は、操作系はデジタル化されているが、術前・術中に得られた術野や画像診断情報のデジタル情報を術者の脳（analog）で判断し、その結果をもとに操作は術者の手で行われているシステムである。一方、後者は、すでにすべてデジタル化されたCAD-CAM (Computer aided design-Computer aided manipulation) surgery system である。本システムによる術中の治療は、取得した術中情報を基に、CADでプランニングを行う。次に、決定した手術手順を基に治療装置をCAMで正確にコントロールする必要がある。

Ⅳ手術工程を管理する外科医の新しい脳

新しい手術器具・システムを疾患の治療に適用する前に、適用疾患の手術工程解析が必要である。従来の術式・手術操作・器具に対し、新たに適用する術式・器具などが全体を考えた上でのメリットがあるかどうかを検証する重要な工程である。手術を一つの生産ラインと考えると、部分最適化による術式や手術器具の改良は別な部位での手術操作のボトルネックを生み出す事になる。全体を考えての術式や器具の最適化が絶対必要である。設定されたゴールを基に、ロボット治療の選択肢を事前に評価して、ロボットにすべきか通常の手術操作にするかの選択を行う。手術計画にしたがって、手術戦略デスクは術中モニターや術中画像情報を収集して、執刀医に最新の手術戦略地図やナビゲーション情報をオンラインで供給する。執刀医は手術戦略地図を使って、操作部位を計画と照合しつつ操作を行うのである。従来の外科手術は、眼前の状況を正しく認識し、状況に応じて実行すべき目標を設定し、上手に手術操作を行うためのスキルが要求されてきた。ここに手術の上手い・下手が存在する。

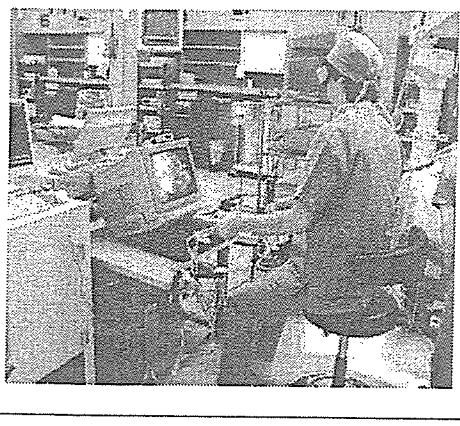
しかし、一定の品質の医療の標準化のためには、従来型の医療システムからの脱却は避けて通れない道である。それを実現するのが、従来の手術デバイスを超えたインテリジェントデバイスとしての精密治療装置と安全にかつ正確に運用し、あらかじめ起こることを予想し、起きる前に対処する先行予測型医療システムである。

Ⅴ開発中の精密手術デバイス

低侵襲手術におけるマニピュレーションの活用が、これからの脳外科手術の鍵である。しかし、人間の手や箸ができることをロボットがしても意味はない。重要なのは、ロボットでしかできないことをすることである。脳外科は、顕微鏡手術から、内視鏡手術に移行する時期に来ている。内視鏡手術においては、内視鏡手術操作に適した微細マニピュレータの開発が必須である。先端1mm、外径3mmの3本のマニピュレータを持った微細マニピュレータは、信州大学、東京女子医科大学、日立製作所と共同で開発され(HUMAN:Hyper Utility Mechatroic AssistaNt)、NeuRobotTMとして、2002年8月に信州大学で世界初の脳外科ロボット手術を実現した。現在までに、4例の臨床研究がなされている[2,3]。オープンMRI対応マニピュレータも開発中である[5-7] (Fig.3)。

レーザーは、1960年代末に手術器具として導入され、

Fig.3 Developing master-slave manipurator



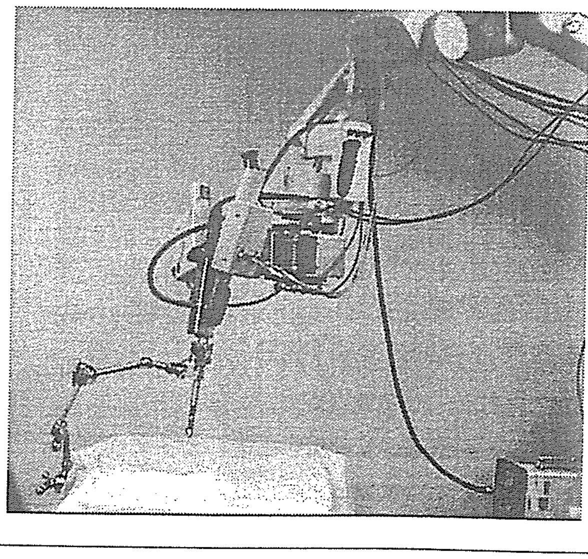
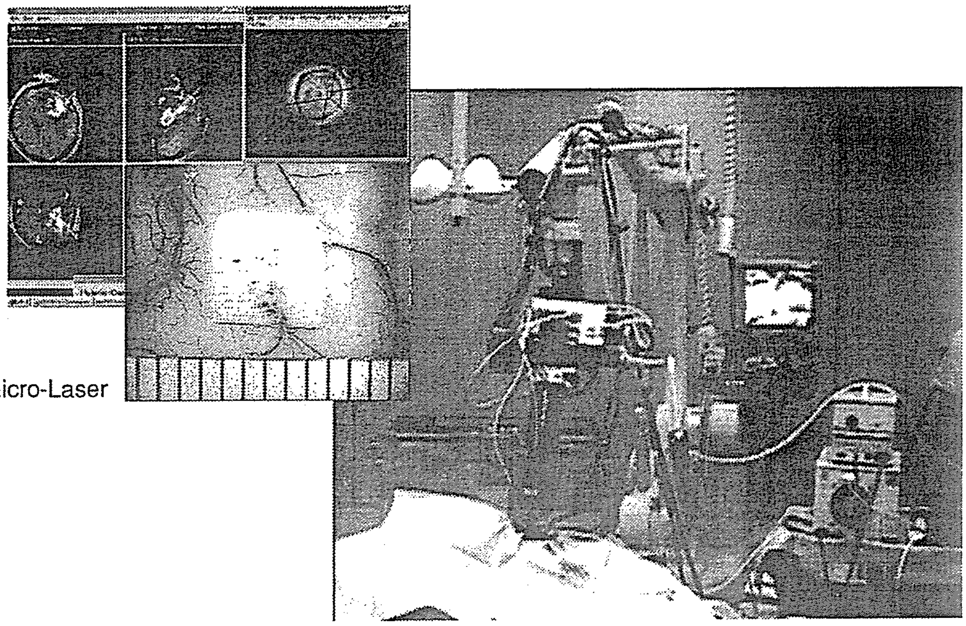


Fig.4 LASER ablation system



脳神経外科でも脳腫瘍などに使われ好成績をおさめている。半導体レーザー（micro Laser）は、照射径が120μmで浸透度が300μmと小さくピンポイントサージェリーに最適である。オートフォーカース機構を組み込んだレーザー照射装置により、eloquent areaのより微細な手術が可能で動物実験の段階であるが、臨床使用も射程距離にある[4-7]（Fig.4）。

探査センサーと治療用システムを統合した、診断・治療融合型マニピュレータ[8]や脳外科用の術野確保マニピュレータとして、水圧駆動式の多関節脳ベラ型も開発されている[9]。

Ⅵおわりに

将来的には、決断のための情報がリアルタイムに更新される術中判断支援システムが整備され、治療行為の結果は即座に診断・評価され、時事刻々の変化に対応した、次の最適な治療行為が提示される仕組みに移行する。これらを実現し支える技術として、術中に病巣と正常組織の境界を峻別するセンサーと、治療を加えるデバイスを一体化したシステムが必須である。将来的には、すべてのプロセスがデジタル化され、外科医の新しい脳は、蓄積されたデータベースを基に、入力された情報の統合と解析を行い、解析結果から最適な選択肢を術者に提示し、デジタル化された操作系を操作するシステムに移行するであろう。

謝　辞

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Original Article

Development of Surgical Manipulator System "HUMAN" for Clinical Neurosurgery

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Abstract

Surgery using manipulator systems for medical treatment has recently attracted considerable attention as a method for realizing certain minimally invasive surgeries. In the field of navel surgery, some manipulator systems for medical treatments are used in Europe and the United States. However, it is inappropriate to apply these systems to neurosurgery because the size of the manipulators is too large, and only one of them can be used in one insertion part. To solve this problem, we developed the manipulator system "HUMAN", which has an insertion part with a diameter of 10 mm and contains one endoscope and three manipulators. In this paper, we propose the concept for realizing minimally invasive surgery, and discuss the mechanism and control of our developed system based on this concept. A clinical application using this system was successfully performed in August 2002, and was successful. Since the manipulator is so small that operation is possible from one small incision, this system is effective in realizing certain minimally invasive neurosurgeries.

Key words Surgical support, Master-slave manipulator system, Neurosurgery, Clinical application

Introduction

The development of minimally invasive surgery, involving as little damage to the body as possible, is strongly desired as a means to alleviate the physical and psychological suffering of patients and to accelerate postoperative recovery. In a form of such surgery known as laparoscopic surgery, a surgical operation is performed using a laparoscope, and surgical tools such as slender forceps are inserted through small incisions. This type of surgery has been popularized rapidly since the first successful laparoscopic cholecystectomy was performed by Muhe et al. in 1985.[1]

Although laparoscopic surgery has the advantage of low invasiveness, the high degree of difficulty in the manipulation of surgical tools is a major drawback of this procedure as compared with open surgery. As an alternative way to safely perform minimally invasive surgery, much attention has recently been directed at the use of surgical manipulators incorporating robot technology. There are several surgical manipulators currently applied to clinical use mainly in Western countries, such as the da Vinci® and ZEUS® systems, which have been fairly well appraised by clinicians for good maneuverability.[2–5]

Realization of minimally invasive surgery has also been pursued in the field of neurosurgery. For example, procedures such as thermal treatment and biopsy using neuro-endoscopes have entered practical use.[6] However, the applicability of this method is limited to simple movements,

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and the reality is that enucleation of tumors and other operations involving delicate and complicated manipulation are normally performed by means of extensive craniotomy and microsurgery under a surgical microscope.[2] The realization of minimally invasive surgery remains a problem to be solved.

As compared with abdominal operations in general, neurosurgery requires considerations regarding the following characteristics: 1) important normal tissues are located densely around the lesion; 2) tissues are prone to damage and susceptible to pressure; 3) the field of operation is limited to a small area; 4) there are strict limitations on the site of the craniotomy providing an approach to the lesion site; and 5) manipulation must be controlled finely and accurately to avoid damage to normal tissues.

To realize minimally invasive surgery that can provide an alternative to conventional craniotomy, we must be able to perform a dexterous surgical operation in which the surgeon can manipulate multiple slender surgical tools inserted through one small cranial opening in such a way that the lesion may be treated accurately without causing pressure or damage to the surrounding normal tissues. Such an extremely delicate surgical operation can not be performed by human hands.

Existing surgical manipulator systems such as da Vinci® and ZEUS® are not suitable for use in neurosurgery, because of the size and configuration of their surgical tools and other devices involved. In these systems, each manipulator consists of a surgical tool at one end and a bulky drive mechanism at the other end, and this structure results in physical interference when multiple manipulators are used in close proximity. To avoid such interference, devices are set up so that the manipulators and the endoscope are inserted into the patient's body through separate incisions. In addition, the surgical tools used in the da Vinci® system have a diameter as large as 11 mm.[3] Due to these factors, it is impossible to insert the set of manipulators needed for treatment through one small cranial opening. If we try to avoid interference by inserting manipulators through more than one cranial opening, it would be difficult to secure the approach route for each surgical tool, and a wide field of operation would be required. This method, therefore, is not appropriate in the field of neurosurgery, where avoidance of pressure on tissues is desired.

To realize minimally invasive surgery in the field of neurosurgery, it is thus required to create a system that allows the insertion of an endoscope and multiple surgical tools through one small cranial opening and supports the delicate and accurate manipulation of these tools. With this consideration in mind, we developed the manipulator system "HUMAN".[7] In August 2002, we succeeded in the world's first clinical application of HUMAN in the field of neurosurgery,[8] and so far have used this system in the treatment of four patients.

Based on the concept of minimally invasive surgery in the field of neurosurgery, this paper describes the mechanism of the HUMAN system developed to realize the use in clinical settings. It also reports the results of our study confirming the practical effectiveness of this system in clinical use.

Minimally Invasive Surgery Using the HUMAN System

The purpose of the HUMAN system is to perform a surgical operation using an endoscope and three manipulators inserted through a cranial opening with a diameter of 10 mm. The target of treatment is a tumor with a volume of about 1 cm^3. While larger tumors need extensive craniotomy, cases of small tumors in this size range are greatly helped by the use of minimally invasive surgery, which is also effective in the improvement of the patient's quality of life (QOL).

This manipulator is capable of performing more finely controlled motions than the human hand and, thus, realizes more delicate surgical treatment. After further development for practical use, this system may be combined with conventional surgery as an advanced surgical instrument supporting delicate operations in about 30% of cases with malignant brain tumors. It will also enable us to treat small tumors in locations that have been inoperable on with conventional methods as well as to perform precise removal of residual tumors located adjacent to functional areas.

Mechanism of the HUMAN System

Fig. 1 shows an external view of the HUMAN

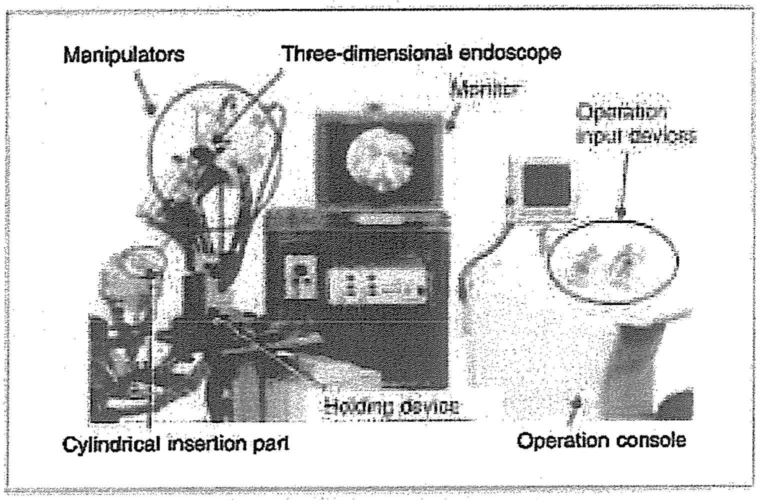

Fig. 1 HUMAN manipulator system

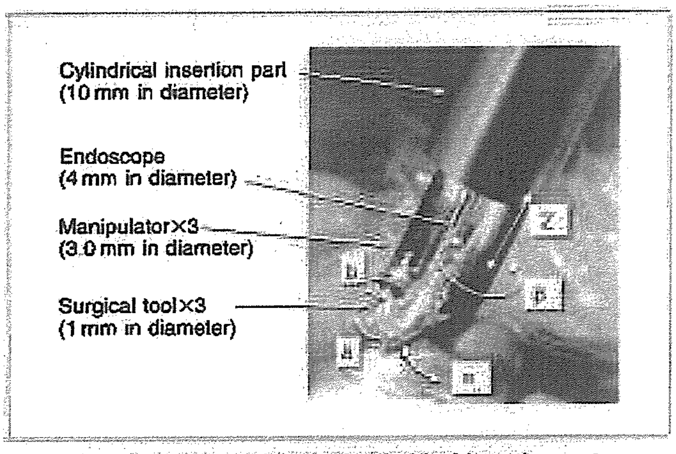

Fig. 2 Magnified image of cylindrical insertion part

system developed by us, and Fig. 2 shows the details of the cylindrical insertion part. While observing the endoscopic image at the center of Fig. 1, the surgeon uses the operation input devices to the right of the figure to perform a surgical operation via the action of the manipulators shown on the left of the figure and in Fig. 2.

The operation input device detects the force applied by the surgeon on the operation lever with a resolving power of 7.8 mN. It controls the position of the operation lever in response to the applied force and prevents movement beyond the range of permitted motion.

The insertion part (with a diameter of 10 mm) consists of a bundle composed of an endoscope (4 mm in diameter) and three manipulators (3 mm in diameter). At the tip of each manipulator is a detachable surgical tool (1 mm in diameter). The spaces in the bundle of the manipulators and endoscope contain five irrigation tubes that can be used for dripping and suction. Each manipulator has three degrees of freedom, corresponding to α (bending), β (rotation), and Z (translation) indicated in Fig. 2. Each surgical tool has a two degrees of freedom, corresponding to a (opening/closing) and b (rotation relative to the joint) in Fig. 2.

Table 1 summarizes the specification values

Table 1 Working area and minimum distance

DOF	α	β	Z
Working area	1/2π rad	2π rad	50 mm
Minimum distance (designed value)	8 μm (α=0 rad)	2 μm (α=π/2 rad)	5 μm

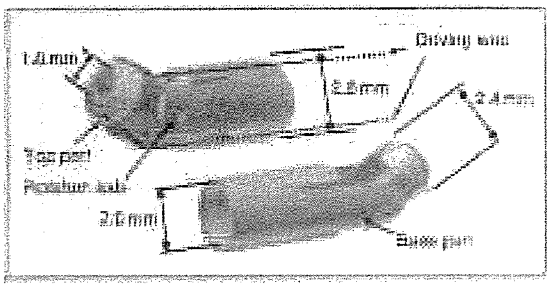

Fig. 3 Hollow micro joint

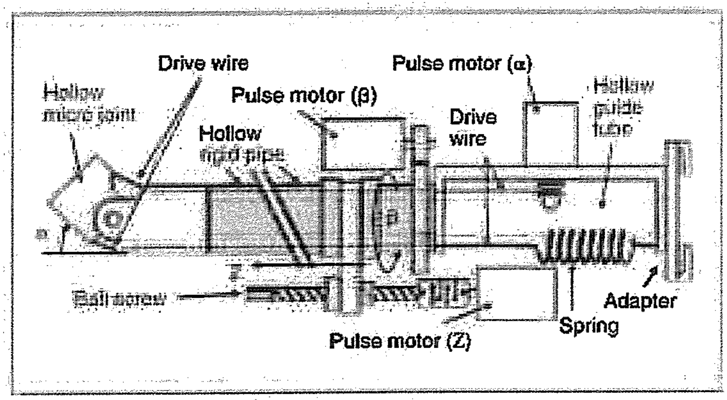

Fig. 4 Drive mechanism of manipulator and micro joint

for the range of movement (working area) and the smallest step of tool-tip movement (minimum distance) in each direction of the three degrees of freedom. Here, the minimum distance refers to the tool-tip displacement resulting from the one-pulse action of the pulse motor used in the manipulator drive mechanism. Because the minimum distances regarding cocking and rotation depend on the cocking angle at the beginning of movement, the Table gives the values corresponding to the positions where the minimum distance would be the largest.

The manipulator drive mechanism and the endoscope are attached to the holding device via an adapter. The holding device inserts the insertion part into the field of operation in response to the surgeon's manipulation. To ensure safety, insertion is performed with the entire manipulator assembly contained within the insertion part. Manipulators extrude from the insertion part when used in treatment.

Fig. 3 shows the structure of the micro-joint in the tip of the manipulator. To realize the miniature moving mechanism, a pair of studs on the top (distal) part has been fitted into corresponding holes in the base part to form a rotation axis. The base part and the top part are designed as hollow tubes with the inside diameters of 2 mm and 1 mm, respectively, so that a surgical tool with a diameter of 1 mm can be housed within the joint.

Fig. 4 shows a schematic illustration of the manipulator drive mechanism. The end of a drive wire, connected to the top part of the micro-joint, is connected to the motor controlling the angle of the joint in the α direction (Fig. 2). This part of the drive mechanism is called the bending unit. Rotation is realized by revolving the hollow rigid pipe together with the micro-joint and the bending unit in the β direction (Fig. 2). Translation is realized by the ball screw producing fine linear motion of the hollow rigid pipe, the bending unit, and the rotation mechanism as a whole in the Z direction (Fig. 2). This structure