Table.1 Naviot™ の経験症例の内訳

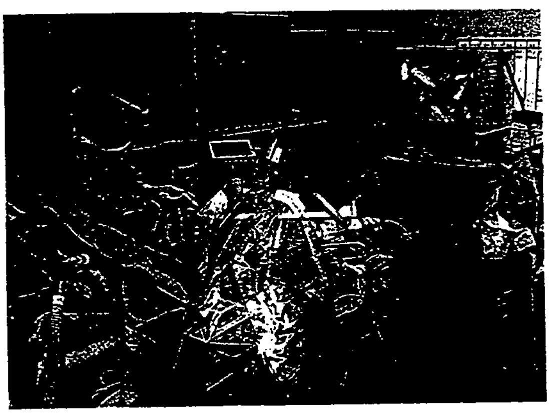
消化器	腹腔鏡下胆嚢摘出術	21
	腹腔鏡下脾臓摘出術	5
	腹腔鏡下鼠径ヘルニア修復術	4
	腹腔鏡下虫垂切除術	1
	腹腔鏡下大腸切除術（大腸癌）	13
	腹腔鏡下 Nissen 術	1
	その他	1
胸	胸腔鏡下両側交感神経切除術	1
	胸腔鏡補助下縦隔腫瘍摘出術	1
	肺葉切除術	1
婦	子宮・卵巣全摘術	8
泌	腹腔鏡下前立腺摘出術	1
	総　合　計	58

標準的な配置として、腹腔鏡下胆嚢摘出術では次のように Naviot™ を配置した。

術者は患者の左側に立ち、この尾側に介助ナースが立つ。助手は術者の対側に、Naviot™ は患者の臍から 400mm～500mm の間に設置した。臍上から内径 12mm の内視鏡用トロカールを挿入した。

4. 結果

全症例で手術は成功した。そのうち胆嚢摘出術において通常の腹腔鏡下手術への移行例が 2 例、脾臓摘出術において開腹移行例が1例、子宮・卵巣全摘術において開腹移行例が1例であった。また、胆嚢摘出術 2 例、ヘルニア修復術 4 例、虫垂切除術 1 例で術者一人による solo-surgery が可能であった。



5. 考察

脾臓摘出術のうち1例は脾腫が著明なため、子宮・卵巣全摘術のうち1例は腹腔鏡下における剥離操作が困難なため開腹に移行した。また、胆嚢摘出術のうち2例はズーム不足のため通常の腹腔鏡下手術に移行した。ズーム式内視鏡のスコープは一般の腹腔鏡に較べ150mmと短いため、臍上からカメラを挿入することで、通常の腹腔鏡下手術へ移行する症例はなくなった。

Naviot™ は子宮・卵巣全摘術、前立腺摘出術などの長時間の手術に置いても助手に変わって手ぶれのない安定した視野を提供でき、ハンドコントロールの術具スイッチによる内視鏡の確実な操作が可能であった。また、ズーム式内視鏡を使用したことで、ヘルニアなどの作業空間が狭い症例でも、鉗子と内視鏡の干渉がなかった。さらに内視鏡先端が汚れにくいため、術中のレンズクリーニングが少なくスムーズな手術が可能であった。

今後の改良点として、ズームイン時の光量不足、ズーム倍率の不足が指摘されていたが、スコープ長を40mm延長することで、奥行き方向へのさらなるアプローチ可能性を検討中である。また、鉗子シャフト部へのコントロールスイッチ装着部材を試作しており、さらなる操作性の向上が期待される。

6. おわりに

Naviot™ は、長時間手術における安定した視野の確保と従来の内視鏡下外科手術の助手を削減することができ、症例によっては solo-surgery が可能であった。医師の人員が限られた環境下では、特に有用と考えられる。

参考文献

(1) Tomikawa M, Hashizume M, Kobayashi E, et al., "Merits of a newly-developed laparoscope manipulator: experiences with 4 cases", CARS2002-H.U.Lemke, M.W.Vannier; K Inamura, A.G.Farman, K.Doi & J.H.C.Reiber (Editors), CARS/Springer, p320-323, 2002

(2) 桃井他，腹腔鏡マニピュレータの臨床適用への検討，日本コンピュータ外科学会論文集，p247-248, 2001

工学と外科の連携

一般外科におけるコンピュータ外科の現状と将来

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はじめに

コンピュータ外科(computer aided surgery または computer assisted surgery；CAS)とは，元々はCT，MRIからの三次元画像作成など，いわゆる医用画像工学の一部を指す用語だったが，その語義は時代とともに拡張し，現在では医用バーチャルリアリティ(virtual reality；VR)，ナビゲーション(画像誘導)手術，手術支援ロボットなどを包括する用語として使われている．医工連携の重要性が認識されることでCASは長足の進歩を遂げ，まったく新しい医療，工学技術が創出され続けている．

近年，米国で開発された完成度の高いda Vinci(Intuitive Surgical社)とZEUS(Computer Motion社)という二つの手術支援ロボットが世に出され，全世界の臨床医に高く評価され急速に普及した．この二つのロボットの登場は臨床医にCASやロボティックサージェリーという新たな分野を認識させる契機となった．我々は高度なナビゲーション機能を有した汎用性の高い手術支援ロボットを，画像工学，精密機械工学，放射線医学や臨床外科学を統合したCASの集大成として研究開発している．

本稿では一般外科医の立場からCASの現状と将来展望を述べ，とくに肝臓を対象として進めている研究の一端を紹介する．

一般外科領域におけるCASの分類

CASは一般外科領域においては，その目的からはおおまかに，治療計画支援，術中支援，治療支援，教育支援に分類される．このほか，全般に関係するヒューマンインターフェイスなどの研究もCASの重要な領域といえる．

治療計画支援

手術計画や結果予測(simulation)がその目的である．CT，MRIやエコー，血管造影などの単独医用画像の画像処理，形状モデリング，および三次元可視化技術などのVR画像は術前診断補助としてはすでに実用領域に入っている．

肝臓は肝動脈，門脈，肝静脈および胆管の四つの脈管系からなる複雑な三次元構造を構築しており，手術適応，手術方針，切除範囲の決定にVR画像が非常に有用である．高機能なVR画像表示ソフトウェアは，腫瘍と周囲脈管との立体的位置関係の把握や，腫瘍や切除肝臓の体積計算(volumetry)にも威力を発揮する．また

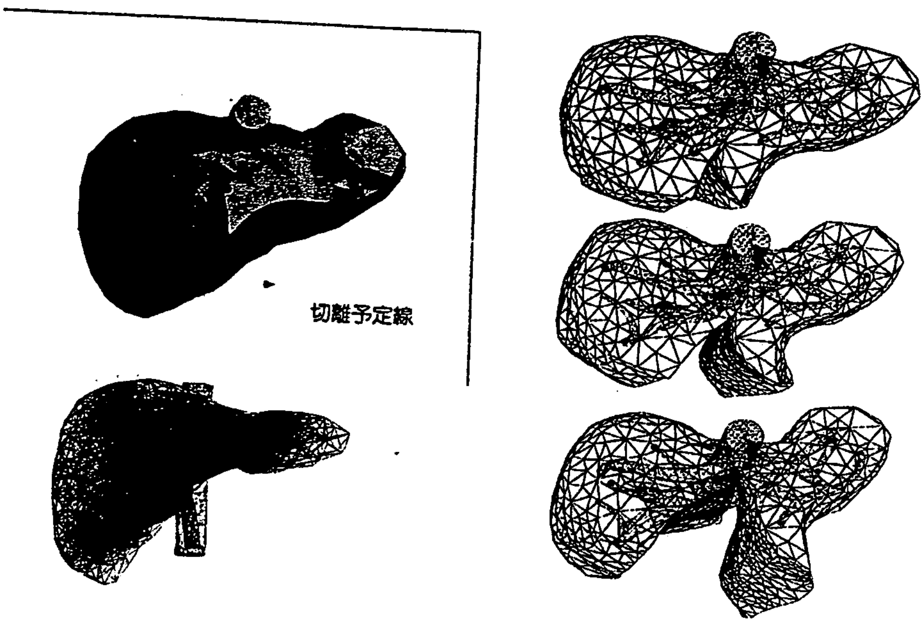

図 1. 肝臓 FEM モデルによる切離シミュレーション

肝切除術や肝移植術だけでなく大腸などの管腔臓器や，血管外科領域の術式の決定にも応用されている．良質な画像の作成には多大な時間と労力を要する弱点もコンピュータの高機能化とソフトウェアの開発によって克服されつつある．このような進歩により手術計画は進歩したが，術中ナビゲーションに応用するためには，術中の臓器変形や環境の変化に対応させるさらに高度な技術が必要となる(後述)．

手術支援―画像誘導手術を中心に―

1. 一般外科領域の手術ナビゲーション

手術ナビゲーションとは，鉗子や焼灼装置などの手術器具を患部に正確に導入するための技術であり，画像処理技術や鉗子や内視鏡の位置を計測する技術や，術前に得られた画像と術中に得られた画像や実画像との重ね合わせ(registration)や臓器変形予測なども含まれる．最近ではアイソトープを利用した sentinel node 探索システムもナビゲーションと呼称されているが，狭義の手術ナビゲーションは画像誘導手術のことを指す．一般外科領域では，術前に得た腫瘍や血管の位置情報は術中操作により変動し，とくに術野の狭い内視鏡手術においては腫瘍や血管の位置を正確に把握することが困難であるため，脳神経外科や整形外科領域に比べてナビゲーションの導入が遅れている．この問題への解決策として，臓器変形シミュレーション，MRI などによる術中イメージング，異種画像を組み合わせたハイブリッド型ナビゲーションなどの研究が行われている．

2. 臓器変形シミュレーション

我々は臓器変形の予測のための有力な手段として，有限要素法[注](finite element method；FEM)を用いて肝臓の術中変形シミュレーショ

注）有限要素法：
複雑な形状・性質をもつ物体(臓器)を単純な小部分(要素)に分割し，その要素の特性を方程式を用いて近似値を表現することにより，物体の変形も計算できる．

ンモデルを，東京大学久田教授(俊明，新領域創成科学研究科)と共同で研究している(図1)．これは肝臓の力学的材料特性を同定し，肝臓のモデル化および術中の状況を想定した変形シミュレーションを行うものである．本法では回転を伴う肝臓の大変形を内部の血管を含めて予測することが可能であり，肝切除の進行に伴う血管位置の変動や露出の様子を予測することもできる．しかし，複雑な計算処理を行うため時間がかかり，まだまだ術中に使用するには至らず，処理の単純化が必要である．

3. 術中イメージング

従来肝臓手術においては，術中エコーが不可欠なものとして日常的に使用されてきたが，画質の面からはCT，MRIが有利である．MRIは，磁場を歪める手術器具の使用ができないという制約はあるが，対応する手術器具が急速に開発されている．被爆が無いことは最大の利点であり，線維走行の可視化や温度計測といった機能画像を提供する能力もあるためMRIが今後の術中イメージングの中心になってくると考えられる．肝臓外科では縮小手術やラジオ波焼灼術などの低侵襲治療が主流となってきており，術中イメージングの役割はますます増大してくる．

4. オーグメンテッドリアリティ(augmented reality；AR)ナビゲーション

ARナビゲーションは，ナビゲーションの画像を術野や腹腔鏡画像に重畳表示させ，術野の非可視化情報を可視化して手術を誘導する技術である．肝臓外科では上述したとおり，エコーが従来より重要な役割を占めてきた．エコーは簡便性，機動性に優れており，肝腫瘍の局在や肝内脈管との位置関係をリアルタイムに表示できるが，客観性などに問題があるため三次元エコーが開発研究されている．我々は腹腔鏡下に三次元エコー画像を取得し，さらにそれを腹腔鏡のライブ画像に重畳表示させて視野移動に追随させるARナビゲーションシステムを，大阪大学田村教授(進一，多元的画像解析分野)と共同で開発している．エコーのみでは計測範囲が狭く低画質であるが，今後はこれにCTなどの術前術中画像を同時使用することで，大幅な機能向上が見込まれる．このように異種の医用画像を組み合わせて弱点を補完するハイブリッド型のナビゲーションシステムは，まさに外科医に新たな目(super eye)を提供するものとして期待される．

治療支援—ロボティクスを中心に—

実際に工学機器の補助によって穿刺や焼灼，手術操作を行う技術である．医療ロボティクス，ロボティックサージェリーなどと呼ばれ，外科医に新たな手(super hand)を提供する技術といえる．現在我が国で一般外科において臨床応用されている手術支援ロボットには以下のものがある．

1. 可動型内視鏡把持装置-NAVIOT(図2)

ズーム式内視鏡を把持したアームを，リンクを介して二つのモーターで駆動する装置であり，内視鏡の視野移動とズームを合わせて3自由度を有している．術者は鉗子に取り付けたコントローラスイッチで内視鏡を制御する．東京大学の土肥教授(健純，情報理工学系研究科)を中心として開発され，我が国初の手術支援ロボットとして2002年5月に厚生労働省の認可を受けた．同様のシステムとしてはボイスコントロールインターフェイスを持つAESOP(Computer Motion社)があり，1994年10月に米国FDAの認可を受けて販売されたが，我が国では音声認識率の低さの問題から爆発的普及には至らなかった．NAVIOTの開発に当たっては各種インターフェイスの比較研究が十分になされた．

2. 内視鏡下手術支援ロボット-ZEUS

ZEUSは1台のAESOPと2本のロボットアームにより構成され，後述するdaVinci同様，三次元内視鏡を備えるMaster-Slave型ロ

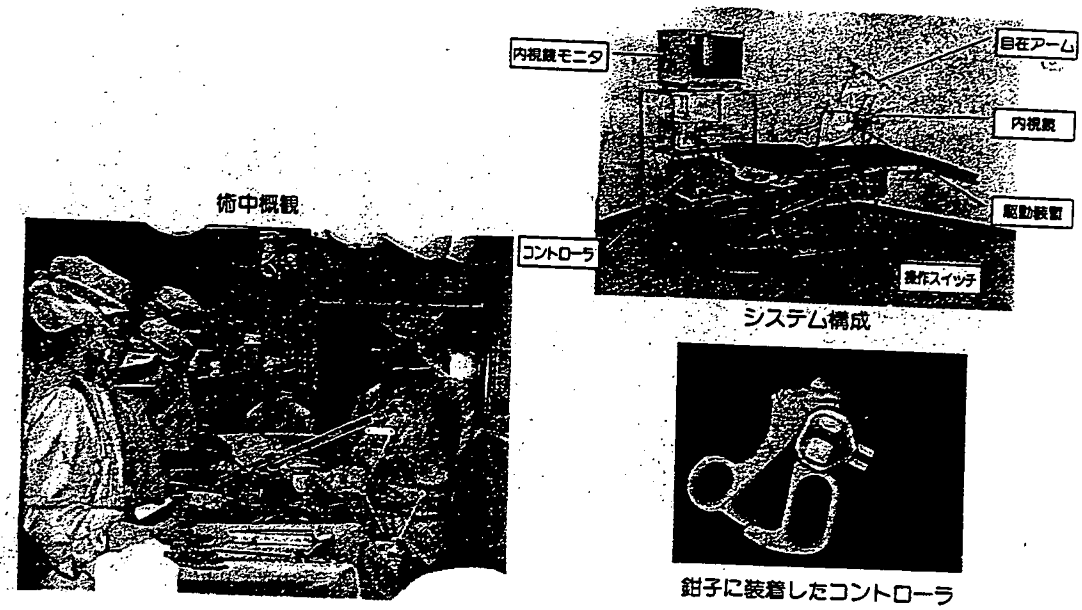

図 2. 可動型内視鏡把持装置-NAVIOT

ボット[注]である．装置は単純，軽量で，セットアップや鉗子の交換が短時間ででき，高い拡張性が利点である．鉗子は3～5 mm とdaVinciより細径であるが，鉗子の動きの器用さは劣る．HERMESというボイスコントロール装置によって内視鏡の操作，手術台や照明の操作などが統合されている．2001 年 9 月に米仏間の遠隔手術(腹腔鏡下胆嚢摘出術)に成功したように遠隔手術への拡張性も高い．

3. 内視鏡下手術支援ロボット-da Vinci

daVinciは，現在最も高度な機能を有し，全体で7自由度を有する操作性の高さが特長である．スケールの変更や振戦の除去機能もあり，縫合･結紮などの微細な手術操作が得意である．1998 年 5 月よりヨーロッパを中心に臨床で使用され，2002 年の時点で 7,000 例を越える心臓手術，消化器外科手術や産婦人科の手術で使用され，良好な手術成績が報告されている．ZEUSより大型で，機動性や拡張性はやや劣る．

このほか，東京大学の光石(衛，工学系研究科)らは遠隔操作が可能な Master-Slave 型ロボットを開発している．スレーブ部に多軸力覚センサを備え，光によるフィードバック機能を備えており，1997 年 7 月に東京一岡山間をインターネットと光ファイバー(1.5 Mbps)で結び血管縫合実験に成功した．2002 年 8 月，我々と共同で東京一静岡間を ISDN3 回線で接続してブタの胆嚢摘出術を成功させた(図 3)．また東京慈恵会医科大学の鈴木(直樹，高次元医用画像工学研究所)，服部(麻木，同)らは，術前画像に基づく三次元画像を daVinci のステレオ画像と AR 表示を行うシステムを，我々と共同で開発している．これらのさまざまな技術を統合することで，最終的に既存のものを超える実用的なシステムの開発を目指している．鍵となるのはナビゲーション機能の実装と小型化である．

注) Master-Slave 型ロボット：
人間の腕･手に相当するロボット部分をマニピュレータといい，操作部分を master，制御される部分を slave という．

図 3. 東京一静岡間のブタ遠隔手術実験

教育支援

手術トレーニング支援や遠隔手術に関する情報伝達などが研究されている．VR 技術を駆使したリアルな血管吻合シミュレータや腹腔鏡操作シミュレータなどが開発されている．医療データベースの整備や地域医療ネットワークなど医療を巡る情報インフラは IT 革命以後，急速に整備が進んでいる．上述したように手術支援ロボットも遠隔手術への応用を前提に開発されており，遠隔手術(tele-surgery)の概念は声による遠隔手術支援(tele-mentoring)からロボットによる遠隔手術操作(tele-manipulating)へと劇的な進化を遂げようとしている．新しい手術支援ロボットが臨床で円滑に機能するためには，医師を含めた医療チームの合理的なトレーニングが重要である．2002 年に九州大学にアジア初の手術支援ロボットのトレーニングセンターが設立された．実際の運用はこれからであるが遠隔手術支援の拠点としても期待されている．

おわりに

CAS の発展によって，手術侵襲の低減，新たな術式の開発，医療費の削減，医工連携による周辺産業の活性化などがもたらされ，その効果は計り知れない．CAS の目的は，人間の限界をコンピュータの介在によって補助ないし拡張していくことであるが，人間である術者が最終決定権を有していることはいうまでもなく，ハードウェアのスペック至上主義に走らず，人に優しい先進医学を創出しなければならない．臨床医学，とくに治療学としての CAS はこれからの分野であり，医学と工学の双方がバランスよく発展を遂げるためには，現場の医師が何を必要としているか，また工学側からはどのような技術的開発が可能であるかを，従来以上に十分に討議し理解することが重要であろう．

文 献

1) Kobayashi E *et al* : A new safe laparoscopic manipulator system with a five-bar linkage mechanism and an optical zoom. Comput Aided Surg **4** : 182, 1999.

2) Hashizume M *et al* : Early experiences of endoscopic procedures in general surgery assisted by a computer-enhanced surgical system. Surg Endosc **16**(8) : 1187, 2002.

3) 光石　衛：テレ-マイクロ-サージェリー. 外科 **61**(3) : 278, 1999.

03(XV)-83

光磁気ハイブリッド三次元位置センサによる鏡視下手術 AR ナビゲーションの開発 –実時間磁場歪み補正の in vivo 精度検証–

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[b]大阪大学大学院医学系研究科多元的画像解析分野

Augmented Reality Navigation System for Laparoscopic Surgery

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Abstract: We have developed an augmented reality navigation system for laparoscopic surgery so far. This system measures the 3D position at the tip of ultrasound probe in abdominal cavity. Although a magnetic tracker is suitable for this purpose, their accuracy is affected by metallic objects such as operating equipments and tables. We have recently proposed the method of precise "real-time" distortion correction of magnetic fields. In this paper, we evaluated the accuracy and validity of this system by the *in vivo* experiment.

Keywords: AR navigation, distortion correction, 3D-US

1. はじめに

腹腔鏡下手術では術中に取得される情報や手術の操作性が限られており、画像誘導(ナビゲーション)は大きな役割を担う。我々はこれまでに、術前および術中に取得した三次元モデルを腹腔鏡の視野移動に連動させ、腹腔鏡の実画像に重畳 (AR: Augmented Reality) 表示するAR腹腔鏡下手術ナビゲーションシステムを開発してきた[1,2]。本システムでは磁気式三次元位置センサで体内の超音波プローブの位置姿勢を計測して三次元超音波画像を作成しているが、手術場環境では手術台や金属製手術器具の影響により磁場に歪みが生じるために無視できない測定誤差が生じる。また、そこで我々は事前の準備を必要とせず簡便な磁場歪みの実時間補正手法を提案した[3]。今回は臨床応用を想定した環境下で動物実験を通して精度検証及び有用性の検討を行ったので報告する。

2. システム概要

システムは光学式三次元位置計測装置 POLARIS(Northern Digital Inc.)、磁気式三次元位置計測装置 miniBIRD(Ascension Technology Inc)、計算機、超音波装置、腹腔鏡装置で構成される(Fig.1)。光学式位置計測装置により、腹腔鏡及び磁気式位置計測装置センサ部の位置を計測する。また磁気式位置計測装置により、磁気式位置計測装置にセンサ部に対する腹腔内の超音波プローブの位置を計測し、同時に内視鏡画像を取り込むことで、三次元超音波画像を構成する。次に、腹腔鏡画像面に対する超音波画像の位置を計測し、術野画像に重畳表示する。

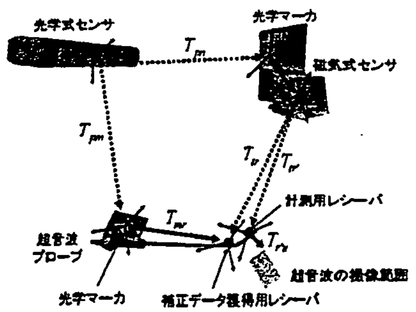

Fig.1: システム各座標系間の関係

3. 歪み補正

歪み補正には術中三次元超音波画像獲得操作の前に予め光磁気双方のセンサを使用し、ラーニングプローブをフリーハンドにて計測範囲をなぞり、実時間にてサンプルデータ取得を行い、磁場歪みを0次から4次までの多項式で近似し、交差検定によって最も補正効果が高い次数を選択する[3]。データ取得操作は約30秒で完了する。なお、センサ自体の精度は、Polaris: 0.35mm RMS、miniBird: 1.8mm RMS である。

4. 実験方法

実験は可及的に手術室と同じ環境を作成して行った。手術台(MIZUHO MOT-5000)とセンサ類との位置関係を Fig.2 に示す。ブタを全身麻酔下に腹腔鏡を挿入気腹し、超音波プローブ、ラーニングプローブは 18mmトロッカーより腹腔内に挿入した。肝臓表面の概ね 10cmx10cmx1cm の計測範囲を何度かスキャンしてサンプリングし、実時間磁場補正のデータを取得した。実験中は呼吸を呼気相にて停止させておいた。

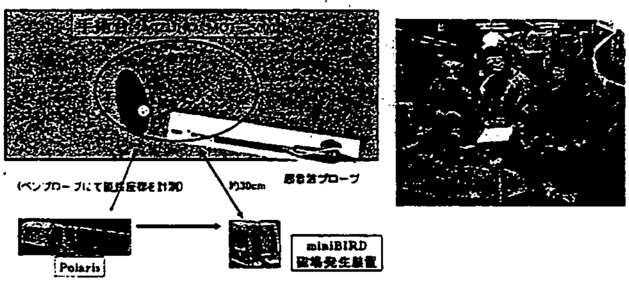

Fig.2:センサ、プローブの配置と実験風景

実験 1. 空間座標測定誤差を計算し、交差検定にて最も補正効果の高い歪み補正近似次数を調べた。

実験 2. ブタ肝下面に接着した直径7mm大の腫瘍ファントムの三次元超音波を取得し、腫瘍の空間座標を、補正の有無、Polarisペンプローブによる直接計測、の3者で比較した。

5. 結果

○実験1:交差検定

1回目

	org	0th	1st	2nd	3rd	4th
position(mm)	10.68	3.33	3.08	3.11	3.16	3.46
angle(degree)	1.81	0.36	0.24	0.23	0.24	0.26

2回目

	org	0th	1st	2nd	3rd	4th
position(mm)	17.01	2.76	1.45	1.61	2.5	3.96
angle(degree)	4.03	0.55	0.23	0.29	0.45	0.73

org は補正なし、0th, 1st, 2nd, 3rd, 4th は補正に用いた多項式の次数を表す。いずれも一次近似が最も補正効果が高かったため、以下一次近似にて補正した。

○実験 2

・ファントムの座標計測値

(A) Polaris : (-30.68, 256.35, -1840.32)
(B) 3DUS (補正あり) : (-36.88, 257.34, -1846.00)
(C) 3DUS (補正なし): (-36.98, 270.64, -1842.45)

・計測値間の距離

(A)-(B):8.45 mm、(A)-(C):15.76 mm、(B)-(C):13.76 mm

歪み補正ありの方がPolaris先端(正解値)に近かった。

・AR 表示の誤差

Polarisペンプローブ先端(黒矢印)に三次元超音波から取得した座標を重ね合わせた(白点:白矢印) 補正ありの方が誤差が少なかった(Fig.3)。

Fig.3:左:歪み補正なし　　右:歪み補正あり

7. 考察

本論文では光磁気ハイブリッドセンサを用いた磁場歪みの実時間補正の効果を臨床とほぼ同じ環境の動物実験で検証した。ファントムでの検討同様、一次近似にて最も良好な歪み補正効果が得られた。AR ナビゲーションの精度評価については、補正後でも 8.45mm とこれまでのファントムでの検討よりも大きな誤差が生じた。これは内視鏡のキャリブレーションなどで生じる誤差以外に肝臓の呼吸性移動や変形が少なからず影響するためと考えられたが、補正なしに比べると確実に誤差は減少していた。また、腫瘍穿刺では内視鏡の視線方向と穿刺点との関係をより厳密に規定する必要もあり、さらなる実験的検討により誤差を少なくする研究が必要と考えられた。臨床への展望として、歪み補正のためのデータ取得操作や計算時間は短時間ですむため現状でも十分実用レベルにあると考えられた。また、厳密な誤差が求められる腫瘍穿刺ではなく、腹腔鏡下胆嚢摘出における総胆管走行の確認や脾臓摘出における脾門部脈管の可視化などで臨床応用し、システム全体の有用性を検討する予定である。

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文献

1. Konishi K, Nakamoto M, Miyamoto M, Hashizume M, Sato Y, Tamura S. "Development of AR Navigation System for Laparoscopic Surgery using Magneto-optic Hybrid Sensor: Experiences with 3 Cases." Proceedings of CARS2002, p1093 2002

2. 中本将彦、山口鉄蔵、中田和久、宮本仁樹、桝本 潤、小西晃造、畦元将吾、橋爪 誠、佐藤嘉伸、田村進一. "斜視鏡に対応した腹腔鏡下手術ナビゲーションシステムの開発" 日本コンピュータ外科学会誌, vol4-3, pp243-244, 2002

3. 中田和久、中本将彦、佐藤嘉伸、小西晃造、橋爪 誠、田村進一 "光磁気ハイブリッド方式による磁気式3次元位置センサの簡便迅速な磁場歪み補正法" 電子情報通信学会論文誌, J86-D-II(1), 2004, 印刷中

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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.

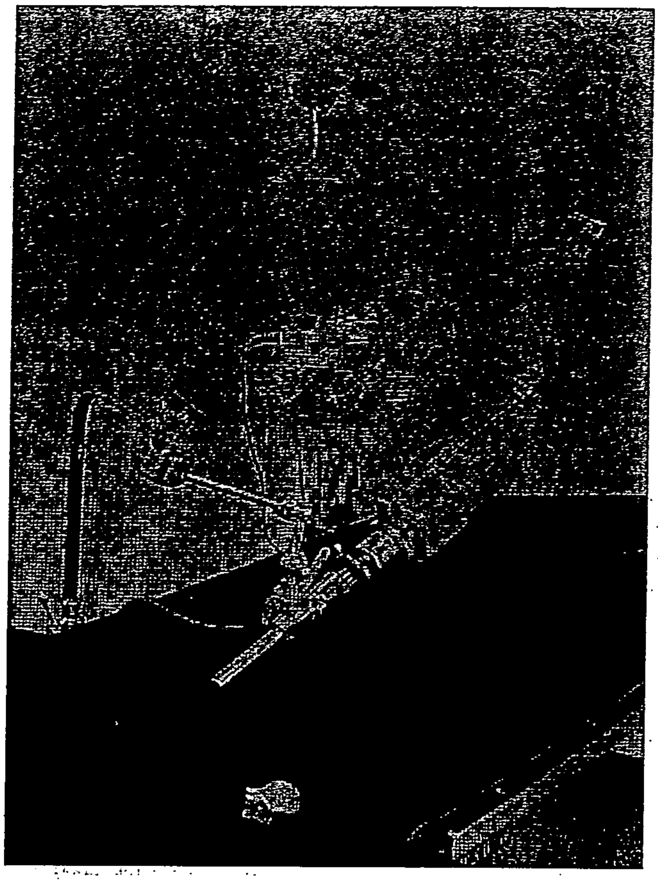

Figure 3. A newly developed laparoscope manipulator, Naviot, is recognized as the first surgical robot developed in Japan.

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.

REFERENCES

1. Sackier JM, Wang Y. Robotically assisted laparoscopic surgery: from concept to development. *Surg Endosc* 1994;8:63–6.
2. Jacobs LK, Shayani V, Sackier JM. Determination of the learning curve of the AESOP. *Surg Endosc* 1997;11:54–5.
3. Johanet H. Voice-controlled robot: new surgical aide? Thoughts of a user. *Ann Chir* 1998;52:918–21.
4. Allaf ME, Jackman SV, Schulam PG, Cadeddu JA, Lee BR, Moore RG, et al. Laparoscopic visual field: voice vs foot pedal interfaces for control of the AESOP robot. *Surg Endosc* 1998;12:1415–8.
5. Lobontiu A. The da Vinci surgical system performing computer-enhanced surgery. *Osp Ital Chir* 2001;7:367–72.
6. Hashizume M, Shimada M, Tomikawa M, Ikeda Y, Takahashi I, Abe R, et al. Early experiences of endoscopic procedures in general surgery assisted by a computer-enhanced surgical system. *Surg Endosc* 2002;16:1187–91.
7. Isgro F, Kiessling A-H, Blome M, Lehman A, Kumle B, Saggau W. Robotic surgery using Zeus microwrist technology: the next generation. *Osp Ital Chir* 2001;7:373–8.
8. Ballantyne GH. Robotic surgery, telerobotic surgery, telepresence and telementoring. Review of early clinical results. *Surg Endosc* 2002;16:1389–402.
9. Hashizume M, Konishi K, Tsutsumi N, Yamaguchi S, Shimabukuro R. A new era of robotic surgery assisted by a computer-enhanced surgical system. *Surgery* 2002;131(1 Suppl):S330–3.
10. Eufinger H, Wittkampf AR, Wehmoller M, Zonneveld FW. Single-step fronto-orbital resection and reconstruction with individual resection template and corresponding titanium implant: a new method of computer-aided surgery. *J Craniomaxillofac Surg* 1998;26:373–8.
11. Weihe S, Wehmoller M, Schliephake H, Hassfeld S, Tschakaloff A, Raczkowsky J, et al. Synthesis of CAD/CAM, robotics and biomaterial implant fabrication: single-step reconstruction in computer-aided frontotemporal bone resection. *Int J Oral Maxillofac Surg* 2000;29:384–8.
12. Federspil PA, Geisthoff UW, Henrich D, Plinkert PK. Development of the first force-controlled robot for otoneurosurgery. *Laryngoscope* 2003;113:465–71.
13. Iseki H, Masutani Y, Iwahara M, Tanikawa T, Muragaki Y, Taira T, et al. Volumegraph (overlaid three-dimensional image-guided navigation). Clinical application of augmented reality in neurosurgery. *Stereotact Funct Neurosurg* 1997;68:18–24.
14. Hata N, Dohi T, Iseki H, Takakura K. Development of frameless and armless stereotactic neuronavigation system with ultrasonographic registration. *Neurosurgery* 1997;41:608–13.
15. Iseki H, Kawamura H, Tanikawa T, Kawabatake H, Taira T, Takakura K, et al. An image-guided stereotactic system for neurosurgical operations. *Stereotact Funct Neurosurg* 1994;63:130–8.
16. Masamuna K, Fichtinger G, Patriciu A, Susil RC, Taylor RH, Kavoussi LR, et al. System for robotically assisted percutaneous procedures with computed tomography guidance. *Comput Aided Surg* 2001;6:370–83.

17. Chinzei K, Hata N, Jolesz FA, Kikinis R. MR compatible surgical assist robot: system integration and preliminary feasibility study. *Lect Notes Comput Sci* 2000;1935:921–30.
18. Sakuma I, Takai Y, Kobayashi E, Inada H, Fujimoto K, Asano T. Navigation of high intensity focused ultrasound applicator with an integrated three-dimensional ultrasound imaging system. *Lect Notes Comput Sci* 2002;2489:133–9.
19. Himpens J, Leman G, Cadier GB. Telesurgical laparoscopic cholecystectomy [letter]. *Surg Endosc* 1998;12:1091.
20. Tomikawa M, Hashizume M, Kobayashi E, Yamaguchi S, Sakuma I, Fujie M, et al. Merits of a newly developed laparoscope manipulator: experiences with 4 cases. In: Lemke HU, Vannier MH, Imamura K, Farman AG, Doi K, Reiber JHC, editors. CARS/Springer 2002;320–3.
21. Kobayashi E, Masamune I, Sakuma I, Dohi Y, Hashimoto D. A new safe laparoscopic manipulator system with a five linkage mechanism and an optical zoom. *Comput Aid Surg* 1999;4:182–92.
22. Yasunaga T, Hashizume M, Kobayashi E, Tanoue K, Akahoshi T, Konishi K, et al. Remote-controlled laparoscopic manipulator system, Naviot™, for endoscopic surgery. *Int Congr Ser* 2003;1256:678–83.
23. Sung GT, Gill IS. Robotic laparoscopic surgery: a comparison of the Da Vinci and Zeus systems. *Urology* 2001;58:893–8.
24. Dakin GF, Gagner M. Comparison of laparoscopic skills performance between standard instruments and two surgical robotic systems. *Surg Endosc* 2003;17:574–9.
25. Lunsford LD. The Presbyterian University Hospital, Pittsburgh. The gamma knife: brain surgery without an incision. *Hosp Physician* 1998;24:28.
26. Drake JM, Joy M, Goldenberg A, Kreindler D. Computer- and robot-assisted resection of thalamic astrocytomas in children. *Neurosurgery* 1991;29:27–33.
27. Carney AS, Patel N, Baldwin DL, Coakham HB, Sanderman DR. Intra-operative image guidance in otolaryngology – the use of the ISG viewing wand. *J Laryngol Otol* 1996;110:322–7.
28. Zamorano L, Matter A, Saenz A, Buciuc R, Diaz F. Interactive image-guide resection of cerebral cavernous malformations *Comput Aided Surg* 1997;2:327–32.
29. Levesque MF, Parker F. MKM-guided resection of diffuse brainstem neoplasm. *Stereotact Funct Neurosurg* 1997;73:15–8.
30. Hongo K, Kobayashi S, Kakizawa Y, Koyama J, Goto T, Okudera H, et al. NeuRobot: telecontrolled micromanipulator system for minimally invasive microneurosurgery–preliminary results. *Neurosurgery* 2002;51:985–8.
31. Goto T, Hongo K, Koyama J, Kobayashi S. Feasibility of using the potassium titanyl phosphate laser with micromanipulators in robotic neurosurgery: a preliminary study in the rat. *J Neurosurg* 2003;98:131–5.
32. Falk V, Diegler A, Walther T, Autschbach R, Mohr FW. Developments in robotic cardiac surgery. *Curr Opin Cardiol* 2000;15:378–87.
33. Shennib H, Bastawisy A, Mack MJ, Moll FH. Computer-assisted telemanipulation: an enabling technology for endoscopic coronary artery bypass. *Ann Thorac Surg* 1998;66:1060–3.
34. Shennib H, Bastawisy A, McLoughlin J, Moll F. Robotic computer-assisted telemanipulation enhances coronary artery bypass. *J Thorac Cardiovasc Surg* 1999;117:310–3.
35. Falk V, Diegler A, Walther T, Loscher N, Vogel B, Ulmann C, et al. Endoscopic coronary artery bypass grafting on the heart using a computer enhanced telemanipulation system. *Heart Surg Forum* 1999;2:199–205.
36. Carpentier A, Louimel D, Aupacie B, Berrebi A, Reliand J. Computer-assisted cardiac surgery [letter]. *Lancet* 1999;353:379–80.
37. Kappert U, Cichon R, Gulielmos V, Schneider J, Schramm I, Nicolai J, et al. Robotic-enhanced Dresden technique for minimally invasive bilateral internal mammary artery grafting. *Heart Surg Forum* 2000;3:319–21.
38. Mohr FW, Falk V, Diegeler A, Walther T, Gummert JF, Bucerius J, et al. Computer-enhanced 'robotic' cardiac surgery: experience in 148 patients. *J Thorac Cardiovasc Surg* 2001;121:842–53.
39. Autschbach R, Onnasch JF, Falk V, Walther T, Kruger M, Schilling LO, et al. The Leipzig experience with robotic valve surgery. *J Card Surg* 2000;15:82–7.
40. Reichenspurner H, Damiano RJ, Mack M, Boehn DH, Gulbins H, Detter C, et al. Use of the voice-controlled and computer-assisted surgical system ZEUS for endoscopic coronary artery bypass grafting. *J Thorac Cardiovasc Surg* 1999;118:11–6.
41. Boehm DH, Reichenspurner H, Gulbins H, Detter C, Meiser B, Brenner P, et al. Early experience with robotic technology for coronary artery surgery. *Ann Thorac Surg* 1999;68:1542–6.
42. Boehm DH, Reichenspurner H, Detter C, Arnold M, Gulbins H, Meiser B, et al. Clinical use of a computer-enhanced surgical robotic system for endoscopic coronary artery bypass grafting on the beating heart. *Thorac Cardiovasc Surg* 2000;48:198–202.
43. Luison F, Boyd WD. Three-dimensional video-assisted thoracoscopic pericardiectomy. *Ann Thorac Surg* 2000;70:2137–8.
44. Grossi EA, Lapietra A, Applebaum RM, Ribakove GH, Galloway AC, Baumann FG, et al. Case report of robotic instrument-enhanced mitral valve surgery. *J Thorac Cardiovasc Surg* 2000;120:1169–71.
45. Okada S, Tanaba Y, Sugawara H, Yamauchi H, Ishimori S, Satoh S. Thoracoscopic major lung resection for primary lung cancer by a single surgeon with a voice-controlled robot and an instrument retraction system. *J Thorac Cardiovasc Surg* 2000;120:414–5.
46. Melfi FM, Menconi GF, Mariani AM, Angeletti CA. Early experience with robotic technology for thoracoscopic surgery. *Eur J Cardiothorac Surg* 2002;21:864–8.
47. Yoshino I, Hashizume M, Shimada M, Tomikawa M, Tomiyasu M, Suemitsu R, et al. Thoracoscopic thymomectomy with the da Vinci computer-enhanced surgical system. *J Thorac Cardiovasc Surg* 2001;122:783–5.
48. Ruurda JP, Hanlo PW, Hennipman A, Broeders IA. Robot-assisted thoracoscopic resection of a benign mediastinal neurogenic tumor: technical note. *Neurosurgery* 2003;52:462–4.
49. Kaiser WA, Fischer H, Vagner J, Selig M. Robotic system for biopsy and therapy of breast lesions in a high-field whole-body magnetic resonance tomography unit. *Invest Radiol* 2000;35:513–9.
50. Veronesi U, Orecchia R, Luini A, Gatti G, Intra M, Zurrida S, et al. A preliminary report of intraoperative radiotherapy (IORT) in limited-stage breast cancers that are conservatively treated. *Eur J Cancer* 2001;37:2178–83.
51. Gianfelice D, Khiat A, Amara M, Belblidia A, Boulanger Y. MR imaging-guided focused US ablation of breast cancer: histopathological assessment of effectiveness – initial experience. *Radiology* 2003;227:849–55.
52. Huber PE, Jenne JW, Rastert R, Simiantonakis I, Sinn HP, Strittmatter HJ, et al. A new noninvasive approach in breast cancer therapy using magnetic resonance imaging-guided focused ultrasound surgery. *Cancer Res* 2001;61:8441–7.
53. Hynynen K, Pomeroy O, Smith DN, Huber PE, McDannold NJ, Kettenbach J, et al. MR imaging-guided focused ultrasound surgery of fibroadenomas in the breast: a feasibility study. *Radiology* 2001;219:176–85.
54. Himpens J, Leman G, Cadiere GB. Telesurgical laparoscopic cholecystectomy [letter]. *Surg Endosc* 1998;12:1091.
55. Cadiere GB, Himpens J, Vertruyen M, Favretti F. The world's first obesity surgery performed by a surgeon at a distance. *Obes Surg* 1999;9:206–9.
56. Cadiere GB, Himpens J, Vertruyen M, Bruyns J, Fourtanier G. Nissen fundoplication done by remotely controlled robotic technician. *Ann Chir* 1999;53:137–41.
57. Cadiere GB, Himpens J. Nissen fundoplication by robot. *Osp Ital Chir* 2001;7:385–92.
58. Degueldre M, Vavdromme J, Huong PT, Cadiere GB. Robotically assisted laparoscopic microsurgical tubal anastomosis: a feasibility study. *Fert Steril* 2000;74:1020–3.
59. Ballantyne GH, Merola P, Weber A, Wasielewski A. Robotic solutions to the pitfalls of laparoscopic colectomy. *Osp Ital Chir* 2001;7:405–12.
60. Weber PA, Merola S, Wasielewski A, Ballantyne GH. Telerobotic-assisted laparoscopic right and sigmoid colectomies for benign disease. *Dis Colon Rectum* 2002;45:1689–94.
61. Ballantyne GH, Hourmont K, Wasielewski A. Telerobotic laparoscopic repair of incisional ventral hernias using intraperitoneal prosthetic mesh. *JSLS* 2003;7:7–14.
62. Meininger D, Byhahn C, Markus BH, Heller K, Westphal K. Total endoscopic Nissen fundoplication with the robotic device 'da Vinci' in children. Hemodynamics, gas exchange and anesthetic management. *Anaesthesist* 2001;50:271–5.
63. Chapman WHH, Albrecht RJ, Kim VB, Young JA, Nifong LW, Chitwood WR Jr. Computer enhanced robotically assisted telemanipulative cholecystectomy [abstract]. *Surg Endosc* 2001;15:S114.
64. Young JA, Chapman WHH, Albrecht RJ, Kim VB, Nifong LW, Chitwood WR Jr. Initial patient series with robotic assisted Nissen fundoplication [abstract]. *Surg Endosc* 2001;15:S175.
65. Melvin WS, Needleman BJ, Krause KR, Scheider C, Wolf RK, Michler RE, et al. Computer enhanced 'robotic' telesurgery: initial experience in foregut surgery [abstract]. *Surg Endosc* 2001;15:S148.

66. Ozawa S, Furukawa T, Ohgami M, Wakabayashi G, Kitajima M. Robot-assisted laparoscopic anti-reflux surgery [abstract]. *Surg Endosc* 2001;15: S152.
67. Melvin WS, Needleman BJ, Krause KR, Wolf RK, Michler RE, Ellison EC. Computer-assisted robotic. Heller myotomy: initial case report. *J Laparoendosc Adv Surg Tech* 2001;11:251–3.
68. Talamini MA, Campbell K, Stanfield C, Are C. Robotic laparoscopic surgery: early lessons learned [abstract]. *Surg Endosc* 2001;15:S165.
69. Cadiere GB, Himpens J, Vertruyen M, Bruyns J, Germany O, Izizaw R. Evaluation of telesurgical (robotic) Nissen fundoplication. *Surg Endosc* 2001;15:918–23.
70. Cadiere GB, Himpens J, Germay O, Izizaw R, Degueldre M, Vandromme J, et al. Feasibility of robotic laparoscopic surgery: 146 cases. *World J Surg* 2001;25:1467–77.
71. Giulianotti PC, Coratti A, Angelini M, Sbrana F, Cecconi S, Balestracci T, et al. Robotics in general surgery: personal experience in a large community hospital. *Arch Surg* 2003;138:777–84.
72. Talamini MA, Chapman S, Horgan S, Melvin WS. A prospective analysis of 211 robotic-assisted surgical procedures. *Surg Endosc* 2003;17:1521–4.
73. Melvin WS, Needleman BJ, Krause KR, Ellison EC. Robotic resection of pancreatic neuroendocrine tumor. *J Laparoendosc Adv Surg Tech A* 2003; 13:33–6.
74. Marescaux J, Smith MK, Folscher D, Jamali F, Malassagne B, Leroy J. Telerobotic laparoscopic cholecystectomy: initial clinical experience. *Ann Surg* 2001;234:1–7.
75. Abbou CC, Hoznek A, Salomon L, Olsson LE, Lobontiu A, Saint F, et al. Laparoscopic radical prostatectomy with a remote controlled robot. *J Urol* 2001;165:1964–6.
76. Young JA, Chapman WH III, Kim VB, Albrecht RJ, Ng PC, Nifong LW, et al. Robotic-assisted adrenalectomy for adrenal incidentaloma: case and review of the technique. *Surg Laparosc Endosc Percutan Tech* 2002;12: 126–30.
77. Hoznek A, Zaki SK, Samadi DB, Salomon L, Lobontiu A, Lang P, et al. Robotic assisted kidney transplantation: an initial experience. *J Urol* 2002; 167:1604–6.
78. Horgan S, Vanuno D, Sileri P, Cicalese L, Benedetti E. Robotic-assisted laparoscopic donor nephrectomy for kidney transplantation. *Transplantation* 2002;73:1474–9.
79. Guillonneau B, Cappele O, Martinez JB, Navarra S, Vallancien G. Robotic assisted, laparoscopic pelvic lymph node dissection in humans. *J Urol* 2001;165:1078–81.
80. Mettler L, Ibrahim M, Jonat W. One year of experience working with the aid of a robotic assistant (the voice-controlled optic holder AESOP) in gynaecological endoscopic surgery. *Hum Reprod* 1998;13:2748–50.
81. Diaz-Arrastia C, Jurnalov C, Gomez G, Townsend C Jr. Laparoscopic hysterectomy using a computer-enhanced surgical robot. *Surg Endosc* 2002; 16:1271–3.
82. Molpus KL, Wedergren JS, Carlson MA. Robotically assisted endoscopic ovarian transposition. *JSLS* 2003;7:59–62.
83. Margossian H, Garcia-Ruiz A, Falcone T, Goldberg JM, Attaran M, Gagner M. Robotically assisted laparoscopic microsurgical uterine horn anastomosis. *Fertil Steril* 1998;70:530–4.
84. Margossian H, Falcone T. Robotically assisted laparoscopic hysterectomy and adnexal surgery. *J Laparoendosc Adv Surg Tech* 2001;11:161–5.
85. Piazza L, Caragliano P, Scardilli M, Sgroi AV, Marino G, Giannone G. Laparoscopic robot-assisted right adrenalectomy and left ovariectomy (case reports). *Chir Ital* 1999;51:465–6.
86. Falcone T, Goldberg JM, Margossian H, Stevens L. Robotic-assisted laparoscopic microsurgical tubal anastomosis: a human pilot study. *Fertil Steril* 2000;73:1040–2.
87. Tempany CM, Stewart EA, McDannold N, Quade BJ, Jolesz FA, Hynynen K. MR imaging-guided focused ultrasound surgery of uterine leiomyomas: a feasibility study. *Radiology* 2003;226:897–905.
88. Stewart EA, Gedroyc WM, Tempany CM, Quade BJ, Inbar Y, Ehrenstein T, et al. Focused ultrasound treatment of uterine fibroid tumors: safety and feasibility of a noninvasive thermoablative technique. *Am J Obstet Gynecol* 2003;189:48–54.
89. Gutt CN, Markus B, Kim ZG, Meininger D, Brinkmann L, Heller K. Early experiences of robotic surgery in children. *Surg Endosc* 2002;16:1083–6.
90. Bentas W, Wolfram M, Brautigam R, Binder J. Laparoscopic transperitoneal adrenalectomy using a remote-controlled robotic surgical system. *J Endourol* 2002;16:373–6.
91. Bentas W, Wolfram M, Brautigam R, Probst M, Beecken WD, Jonas D, et al. Da Vinci robot assisted Anderson–Hynes dismembered pyeloplasty: technique and 1 year follow-up. *World J Urol* 2003;21:133–8.
92. Le Bret E, Papadatos S, Folliguet T, Carbognani D, Petrie J, Aggoun Y, et al. Interruption of patent ductus arteriosus in children: robotically assisted versus videothoracoscopic surgery. *J Thorac Cardiovasc Surg* 2002;123: 973–6.
93. Lorincz A, Langenburg S, Klein MD. Robotics and the pediatric surgeon. *Curr Opin Pediatr* 2003;15:262–6.
94. Rotteleur G, Mordon S, Buys B, Sozanski JP, Brunetaud JM. Robotized scanning laser handpiece for the treatment of port wine stains and other angiodysplasias. *Lasers Surg Med* 1988;8:283–7.
95. McDaniel DH. Cutaneous vascular disorders: advances in laser treatment. *Cutis* 1990;45:339–60.
96. Handels H, Ross T, Kreusch J, Wolff HH, Poppl SJ. Computer-supported diagnosis of melanoma in profilometry. *Methods Inf Med* 1999;38:43–9.
97. Handels H, Ross T, Kreusch J, Wolff HH, Poppl SJ. Image analysis and pattern recognition for computer supported skin tumor diagnosis. *Medinfo* 1998;9:1056–62.
98. Iddan G, Meron G, Glukhovsky A, Swain P. Wireless capsule endoscopy. *Nature* 2000;405:417.
99. Meron GD. The development of the swallowable video capsule (M2A). *Gastrointest Endosc* 2000;52:817–9.
100. Costamagna G, Shah SK, Riccioni ME, Foschia F, Mutignani M, Perri V, et al. A prospective trial comparing small bowel radiographs and video capsule endoscopy for suspected small bowel disease. *Gastroenterology* 2002;123:999–1005.
101. Scapa E, Jacob H, Lewkowicz S, Migdal M, Gat D, Gluckhovski A, et al. Initial experience of wireless-capsule endoscopy for evaluating occult gastrointestinal bleeding and suspected small bowel pathology. *Am J Gastroenterol* 2002;97:2776–9.
102. Bardan E, Nadler M, Chowers Y, Fidder H, Bar-Meir S. Capsule endoscopy for the evaluation of patients with chronic abdominal pain. *Endoscopy* 2003;35:688–9.
103. Fireman Z, Mahajna E, Broide E, Shapiro M, Fich L, Sternberg A, Kopelman Y, et al. Diagnosing small bowel Crohn's disease with wireless capsule endoscopy. *Gut* 2003;52:390–2.
104. Hollerbach S, Kraus K, Willert J, Schulmann K, Schmiegel W. Endoscopically assisted video capsule endoscopy of the small bowel in patients with functional gastric outlet obstruction. *Endoscopy* 2003;35:226–9.
105. Eliakim R, Fischer D, Suissa A, Yassin K, Katz D, Guttman N, et al. Wireless capsule video endoscopy is a superior diagnostic tool in comparison to barium follow-through and computerized tomography in patients with suspected Crohn's disease. *Eur J Gastroenterol Hepatol* 2003;15:363–7.
106. Saurin JC, Delvaux M, Gaudin JL, Fassler I, Villarejo J, Vahedi K, et al. Diagnostic value of endoscopic capsule in patients with obscure digestive bleeding: blinded comparison with video push-enteroscopy. *Endoscopy* 2003;35:576–84.
107. Ang TL, Fock KM, Ng TM, Teo EK, Tan YL. Clinical utility, safety and tolerability of capsule endoscopy in urban Southeast Asian population. *World J Gastroenterol* 2003;9:2313–6.
108. Zuckerman GR, Prakash C, Askin MP, Lewis BS. AGA technical review on the evaluation and management of occult and obscure gastrointestinal bleeding. *Gastroenterology* 2000;118:201–21.
109. Gay GJ, Delmotte JS. Enteroscopy in small intestinal inflammatory diseases. *Gastrointest Endosc Clin N Am* 1999;9:115–23.
110. Nolan DJ, Traill ZC. The current role of the barium examination of the small intestine. *Clin Radiol* 1997;52:809–20.
111. Johnson A. Laparoscopic surgery. *Lancet* 1997;349:631–5.
112. Ota DM. What's new in general surgery: surgical oncology. *J Am Coll Surg* 2003;196:926–32.
113. Hubert J, Feuillu B, Mangin P, Lobontiu A, Artis M, Villemot JP. Laparoscopic computer-assisted pyeloplasty: the results of experimental surgery in pigs. *BJU Int* 2003;92:437–40.