

また、内視鏡や術具を、胎盤や羊膜の損傷を避けながらターゲットへと導くことを目的として、超音波診断装置を併用した術中ナビゲーション技術の開発も進めている。

(3)治療支援デバイス

子宮にあけた 3-4mm の切開口から挿入し、より高い操作性を実現するための術具・デバイス開発を進めている。日本原子力研究所・ペンタックス株式会社では、治療用レーザーファイバと観察用ファイバを一本に統合した複合光ファイバの開発が進められている。これにより、ターゲットを視野中心に観察しながらレーザー焼灼を行うことが可能となる。

また、術具先端に高い自由度を持たせるための極細径多自由度手術ロボット鉗子の開発も進められている。東京大学ではリンク駆動式³⁾、早稲田大学ではワイヤ駆動式⁴⁾の極細径多自由度マニピュレータを開発しており、双胎間輸血症候群のレーザー手術、二分脊椎症胎児期修復術への応用を考えている。いずれも内部が中空であることから、上記の複合光ファイバを挿入することも検討されている。

上記の、(1)術前診断、(2)術中観察・ナビゲーション、(3)治療支援デバイスの分野で開発された技術を統合することで、胎児手術支援の統合システムを開発していく。

4. まとめと今後の展望

本報告では、双胎間輸血症候群(TTTS)と二分脊椎症を対象とした手術支援デバイス開発を中心に述べた。今後は横隔膜ヘルニア、胎児心疾患についても技術開発が進むものと考えられる。

胎児外科を対象とする工学的支援には様々な制約があり、技術開発には多くの困難を伴う。しかしながら、胎児外科用に開発された技術を術中制約のより少ない他分野へ応用・展開していくことは比較的容易であり、今回の開発技術の汎用化やコンピュータ外科の今後の発展に大いに寄与すると期待する。

謝辞

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文献

- 1) T.Chiba, M.R.Harrison, C.T.Albanese and D.L.Farmer, "Fetal Surgery: Past, Present, and Future", Fetal Surgery Japan Society of Prenatal and Neonatal

Medicine, Vol.36, No.4, pp.524-539, 2000

- 2) Enrico Danzer, Roman M. Sydorak, Michael R. Harrison, Craig T. Albanese, "Review Minimal access fetal surgery", European Journal of Obstetrics and Gynecology and Reproductive Biology, Vol.108, 3-13, 2003
- 3) 山下紘正, 他: 多節スライダ・リンク機構を用いた腹部外科手術用鉗子マニピュレータの開発, 日本コンピュータ外科学会誌, Vol. 5, No. 4, pp. 421-427, 2004
- 4) 原田香奈子, 坪内広太, 千葉敏雄, 藤江正克, Open-MRI 下における低侵襲胎児手術用マニピュレータの開発, 第 13 回日本コンピュータ外科学会論文集, pp.111-112, 2004

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Multi-DOFs Bending Manipulator for Intrauterine Surgery

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Abstract: This paper proposed multi-DOFs miniature manipulator for intrauterine surgery, especially for twin-to twin transfusion syndrome (TTTS). Recent therapy for this case requires endoscopic approach toward anastomotic vessels on the placenta, therefore, we developed newly designed 2-DOFs bending mechanism. Each DOF bending mechanism consisted of 3 frames and 2 links with simple driven procedure from -90 to $+90$ degrees, which was suitable for a miniature constitution to minimize invasion of patients. Three frames are jointed with 2 guide wires preventing slip of frames in bending motion. Outer diameter of 2-DOFs bending manipulator was 3.5mm and center channel diameter was 0.8mm to work various end-effectors. In laser ablation experiments using phantom model of placenta, we confirmed that this miniature manipulator enabled laser ablation with bending motion of maximum 66 degrees in the water. In conclusion we were sure of feasibility of the miniature manipulator to enable laser ablation with 2-DOFs bending motion for therapy of TTTS in clinical applications.

Key words: Twin-to-twin transfusion syndrome, Multi-DOFs miniature manipulator, Intrauterine surgery

1. はじめに

双胎間輸血症候群 (Twin-to-twin transfusion syndrome: TTTS) は一卵性一絨毛膜性双胎において両児の胎盤循環の血管吻合に起因して生じる症候群であり, 近年の内視鏡下胎児外科手術の発展によって高度な治療が期待される症例である. しかし内視鏡的な胎盤表面へのアプローチは胎盤や吻合血管の位置によって適応が難しい場合が多く, 子宮内で自由にアプローチ方向を操作できる細径の手術器具の開発が求められている. そこで本研究では多自由度を有し, かつ母体への損傷を最小に抑えるため, 細径のマニピュレータの開発を行なう.

2. 転動を利用した1自由度屈曲機構

胎児外科を対象とするため, 従来の腹部外科用マニピュレータに採用した多節スライダ・リンク機構¹⁾に大幅な改良を加えた. Fig. 1に示す1自由度屈曲機構の基本原理により, 少ない構成要素で $\pm 90^\circ$ 駆動範囲の実現が可能になる (Fig. 2). Frame1 と Frame3 は互いに向き合う円弧面 Arc1, Arc2 が接するように Frame2 を介して連結される. Frame2 は Link1, Link2 のスライダ運動によりモーメントを与えられ Frame3 周りに回転し, 同時に Frame1 上の円弧 Arc1 が Frame3 上の円弧 Arc2 の周りを外サイクロイドの軌道を描きながら転がり運動をする. Arc1 と Arc2 の半径が一致する場合, リンクのスライダ運動により Frame2 が Frame3 に対して θ だけ回転した際, Frame1 も Frame2 の周りに θ だけ回転するため, 合計 2θ の回転角度を得ることができる.

ここで Link1 と Link2 を連結する Link joint のスライダ変位量 x と Frame2 の回転角度 θ の関係は, Fig. 1 中に示した各構成要素の寸法を用いて, 式(1)で表すことができる.

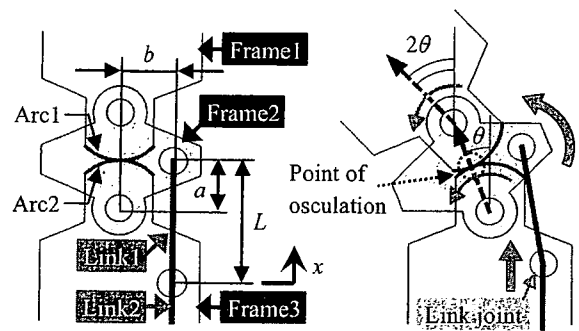


Fig. 1 Basic concept of 1-DOF bending mechanism. Left is component and dimension of the mechanism. Right is rolling of Frame1 around Frame3 jointed with Frame2 by linear motion of Link joint.

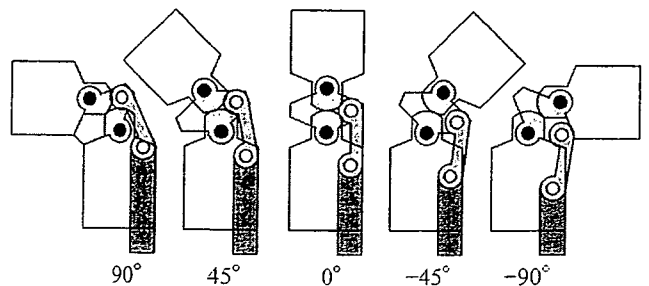


Fig. 2 Bending procedure of 1-DOF mechanism from -90 to $+90$ degrees.

$$x = L + a(\cos \theta - 1) + b \sin \theta - \sqrt{L^2 - 2(a^2 + b^2)(1 - \cos \theta) + \{a(\cos \theta - 1) + b \sin \theta\}^2} = f(a, b, L, \theta) \quad (1)$$

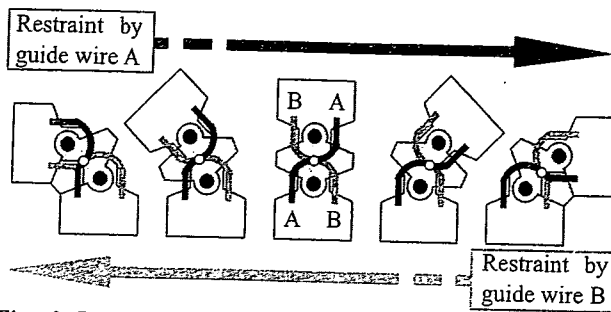


Fig. 3 Restraint mechanism with two guide wires realizes 1-DOF stable bending procedure.

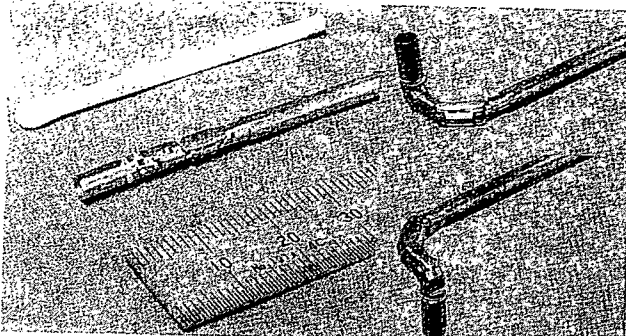


Fig. 4 Left is scale of the manipulator tip. Right are 2-DOFs bending shapes of the manipulator by independent motions.

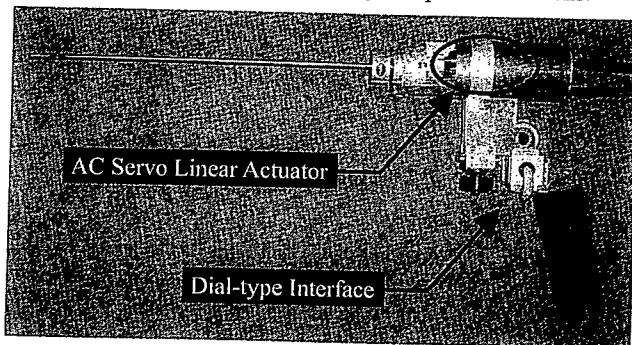


Fig. 5 View of the 2-DOFs miniature manipulator.

Frame1 と Frame3 の円弧面は Frame2 をはさみ、互いに滑りを生じない構造にする必要がある。そこで本マニピュレータでは外径を可能な限り細くするため、極細のワイヤロープ（朝日インテック株式会社、G-15）をガイドとして用いた。Fig. 3 に示すように、Frame1 と Frame3 を 2 本のワイヤロープで連結することで±両方向の屈曲に対し、滑りを生じることなく±90° の駆動範囲を実現している。

3. 2 自由度屈曲細径マニピュレータ

前項で示した 1 自由度屈曲機構を 2 個、前後 1 列に連結することで、垂直・水平方向に屈曲が可能な外径φ3.5mm の 2 自由度屈曲マニピュレータを構成した (Fig. 4)。なお、マニピュレータの円筒方向の中心にはφ0.8mm のエンドエフェクタ用チャンネルを設けている。また、自由度の駆動には AC サーボリアアクチュエータ (株式会社千葉精密, MASC-D16H06) を用い、実験用としてダイヤル式の操作インタフェースを取り付けている (Fig. 5)。



Fig. 6 Left is laser ablation of phantom model of placenta (chicken cut) with bending motion of the miniature manipulator. Right is laser ablated scars.

4. レーザ焼灼実験

TTTS の治療法としては胎盤吻合血管のレーザー焼灼術の優位性が報告されているため²⁾、本マニピュレータのエンドエフェクタとしてコア径φ0.4mm、外径φ0.7mm のレーザーファイバ (E-6100-B, Dormier MedTech, Germany) を搭載し、鶏肉片を胎盤に模したファントム焼灼実験を行なった。焼灼には Nd:YAG レーザ (固体連続波レーザー) を用い、臨床での使用に合わせて 50 W、1 秒間照射に設定した。また胎児の環境に合わせ、ファントムは水中に固定し、マニピュレータを屈曲させながら焼灼を行なった (Fig. 6)。

本マニピュレータは水平・垂直方向にそれぞれ±90° の屈曲自由度を有するが、ファイバを通した状態で最大 66° まで屈曲させることができた。小さな曲率半径で屈曲させた状態であっても、ファントムのレーザー焼灼には支障はなく、実用化に耐えうる屈曲性能を有することを確認した。なお、屈曲角度が 90° に達しなかったのはファイバの剛性に因るところが大きいが、マニピュレータの曲率半径、そして屈曲の発生力を調整することにより、レーザーの焼灼能力を落とすことなく、より大きな屈曲角度を実現できると考えられる。

5. 結論

本研究では新たに考案した屈曲機構を採用し、胎児外科手術用多自由度屈曲マニピュレータを開発した。また、TTTS の治療に必要なレーザー焼灼のファントム実験を行い、大きく屈曲させながら鳥肉片を凝固させることができた。

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文献

- 1) 山下紘正, 他: 多節スライダ・リンク機構を用いた腹部外科手術用鉗子マニピュレータの開発, 日本コンピュータ外科学会誌, Vol. 5, No. 4, pp. 421-427, 2004
- 2) Senat MV, et al.: Endoscopic laser surgery versus serial amnioreduction for severe twin-to-twin transfusion syndrome. N Engl J Med, 351(2) pp. 136-44, Jul 8 2004

胎児手術用吸引型スタビライザの開発

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Development of a suction stabilizer for fetal surgery

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Abstract: This paper proposes a stabilizer for fetal surgery. This stabilizer aiming for restricting fetal is strongly required in fetal surgery, because fetus is floating in uterine in unstable posture during the fetal surgery. In this research, stabilizer is developed based on the acknowledgement of physical properties of fetal skin. Stabilizer is consisted of flame part and suction part. Flame part is aiming for holding the suction parts and has 4 DOF (degrees of freedom) and the tip has make-and-break mechanism. Suction part as effective part is made by silicone not to injure fetus and has holes to aspirate. In the future, drive unit and suction part is evaluated and improved through several experiments.

Key words: Fetal surgery, Stabilizer, Myelomenigocele, silicone, Skin

1. 序論

胎児治療とは、産科的超音波診断など出生前診断技術の著しい進歩とともに、近年注目されてきた分野である。本稿にて注目した二分脊椎症は、脊椎が羊水中に露出することで出生後の障害レベルが悪化するものであり、早期の治療が必要とされている。また、早期治療が可能であればその分回復も早く出生時における胎児の状態も好ましい。従来の手術方法は開腹手術であるが、胎児手術特有のリスクが大きいため、その代替として内視鏡下で手術を行うことが望まれている。しかし、開腹手術同様にその手技は非常に難しい¹⁾²⁾。胎児手術における内視鏡手術の特徴は以下が挙げられる。

- 1) 対象となる患部の大きさが 10mm 四方程度と小さく、非常に脆弱であること
- 2) 胎児が羊水内に浮遊しており定まった体位を維持しがたいこと
- 3) 胎盤の位置によって子宮に挿入する術具の位置が制限されること
- 4) 混濁した羊水中では内視鏡の視野が不明瞭で、しかも内視鏡と超音波診断の組み合わせによる 2 次元画像に依存していること
- 5) 羊水中では通常使用する手術機器(電気メス、超音波メスなど)のパフォーマンスが十分発揮できないこと
- 6) 手術に時間がかかること

本研究では Fig.1 に示すような、小さな切開から進入して胎児を固定するスタビライザと、処置を行う小型マニピュレータで構成される低侵襲手術支援システムを構想に、胎児を固定するためのスタビライザを開発することを目的とした。スタビライザを開発にあたり、直接対象患部の操

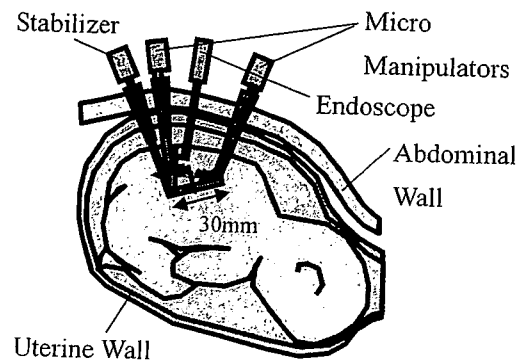


Fig.1 fetal surgery

作を行うという点から 1)の課題を解決するために、対象の患部の特性を得るため粘弾性試験機を用いたクリープ試験及び組織観察を行った³⁾。本報告では、その結果をもとにスタビライザの試作を行った。

2. スタビライザ試作機

2.1 要求仕様

スタビライザの要求仕様を求めるために、対象部位となる胎児皮膚の基礎実験を行った。実験材料にはラット胎児皮膚を模擬材料として用い、力学的特性試験及び応力負荷後の皮膚の組織観察を行った。力学的特性結果では、皮膚が 4kPa 以上の応力で破断し、応力を複数回かけた場合にも変位の大きさが大きく変わらなかった。また、組織観察結果から、手術時に皮膚に損傷があっても出生前までに基底層が新しい皮膚を作り出し回復する見込みがあると考えられる。よって 4kPa 以下の負荷であれば繰り返し負荷をかけた場合でも皮膚の基底層に損傷が見られず、よって皮膚が負荷に耐えうるということがわかった。

2.2 フレーム部

2.1項で求めた対象皮膚の特性をもとに、スタビライザを試作した。スタビライザは大きく、2つの部位に分かれており、フレーム部と吸着部がある。吸着部に関しては次項で述べる。

スタビライザのフレーム部を Fig.2 に示す。シャフト径は胎児手術用のトロカーに対応し、直径 3mm 以下とした。また、対象患部の大きさが 10mm×10mm であることから、本試作機では先端の固定面積を大きめにとり、30mm×30mm とした。そのため先端吸着部の大きさは 30mm とし、さらに先端部は 3mm の細い穴を通った先で広がり、胎児を固定する必要があるため、Fig.2 に示すようなシンプルな形状の開閉機構とした。開閉は 90 度まで可能である。さらに胎盤が切開部から直線的にアプローチ可能な範囲外にあるとき(腹部側にある場合)を想定して屈曲 1 自由度を設けた。また、先端部での固定は胎児への低侵襲性を考慮して、吸着による固定とし、そのためシャフト内には開閉と屈曲の 2 自由度を駆動するための伝達機構のほかに吸着用チューブ(直径 1mm)が通す必要がある。このため、比較的大きなトルクが必要と考えられる屈曲部はリンクによる駆動方式を採用し、先端部の開閉はワイヤで行うこととした。

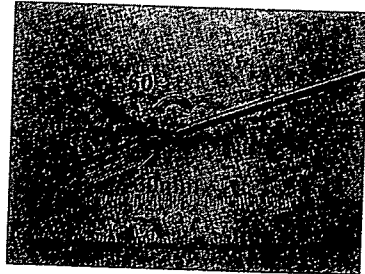


Fig.2 stabilizer frame

2.3 吸着部

本研究で開発するスタビライザにおいて重要視されるのが、脆弱な胎児の固定方法である。対象が胎児であるため、脆弱性を考慮し、押し付けによる固定など負荷が大きくなる手段は避け、吸着による固定とした。また、吸着部の材料には生体適合性が高く、かつ柔らかいシリコンを用いることとした。これにより接触面が柔らかく、胎児に対して安全に固定が可能である。

シリコンでの吸着部作成において、以下の 3 点がポイントになる。

- 1) チューブとシリコン部の接合が困難であること
- 2) 吸引のためにシリコン部長手方向に直径 0.5mm の穴を設けること
- 3) 吸引口として、0.5mm×2mm の穴を設けること

以上の問題点を解決するため、Fig.3 に示すような型を作成し吸着部を作成する。下型にシリコンを流し込み、上型に突起を設け、蓋をすることで吸引口を作成した。また長手方向の直径 0.5mm の穴の作成に関しては直径 0.5mm のゲージ管を直径 1mm のシリコンチューブ

ブの中に通した上で一体加工することで解決した。先端は型からはずした後に塞ぐこととする。試作したスタビライザの全体図を Fig.4 に示す。

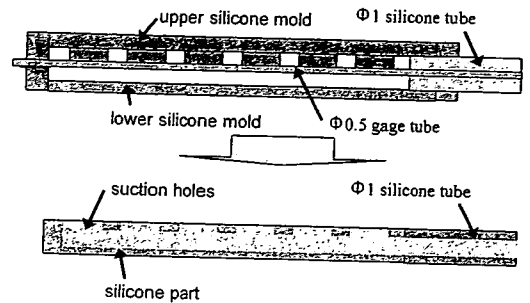


Fig.3 suction part and the mold

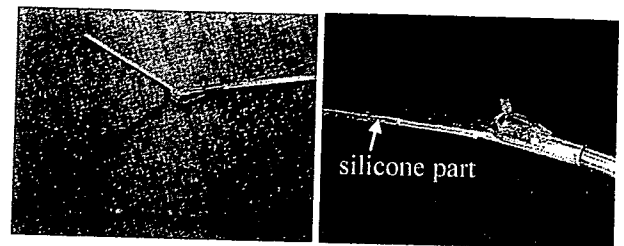


Fig.4 stabilizer and suction part

3. 結言

胎児内視鏡手術において安全に手術を行うための手術支援システムを提案し、胎児を固定するためのスタビライザを試作した。対象となる胎児の皮膚の特性試験及び試験後の皮膚の組織観察をラットの胎児の皮膚を用いて行った結果をもとに、スタビライザのフレーム部及び吸着部を作成した。今後は、試作したスタビライザを使用し、駆動試験及び吸着実験を行うことで評価・改良する。

4. 謝辞

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5. 参考文献

- 1) T.Chiba, M.R.Harrison, C.T.Albanese and D. L.Farmer : Fetal Surgery, Japan Society of Perinatal and Neonatal Medicine Vol36 No4
- 2) Oran S.Aaronson, Noel B.Tulipan, Robert Cywes, Hakan W.Sundell, Georges H.Davis, Joseph P.Bruner and William O.Richards : Robot-Assisted Endoscopic Intrauterine Myelomeningocele Repair: A Feasibility Study, Pediatric Neurosurgery Vol.36,pp85-89,2002
- 3) 坪内広太, 原田香奈子, 千葉敏雄, 絵野沢伸, 藤江正克:“胎児手術用スタビライザの開発”, 第 13 回日本コンピュータ外科学会大会論文集, pp.113-114,2004-12

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Abstract: Identical twins with only one placenta can suffer from twin-twin transfusion syndrome (TTTS) which cause disproportional blood flow from one baby to the other through connecting blood vessels in their placenta. This leads to little blood (anemia) and little amniotic fluid for "donor" fetus and too much blood and too much amniotic fluid for "recipient" fetus. If TTTS occurs early in pregnancy, it could result in loss of both fetuses. For the treatment of TTTS, endoscopic laser coagulation was introduced to separate the connecting vessels in the placenta. This therapy improves fetal survival chances, but it is difficult to maneuver laser tip vertically to the placenta especially when the placenta attaches to the ventral side of the uterus. Therefore, a laser coagulation micro manipulator is proposed and its handheld prototype is developed. The manipulator has four ball joints with through-holes inside. It bends through 50 degrees in any direction at 10 mm from its tip. Though the big bending radius of the laser fiber itself limited the manipulator's bending angle, the prototype demonstrated the possibility of less invasive intrauterine fetal surgery with robotic technology.

Key words: Surgical robot, Fetal surgery, Twin-twin transfusion syndrome, Intrauterine repair

1. 背景

本研究では、胎児手術¹⁾のうち、双胎間輸血症候群 (TTTS)²⁾³⁾を対象とした胎盤吻合血管のレーザ凝固術を対象とする。双胎間輸血症候群は一絨毛膜二羊膜性双胎(胎盤が1つ, 羊膜は二つ)に対して10~15%の割合で生ずる疾患であり、胎盤表面の吻合した血管を通じて二児の血流にアンバランスが生じる。受血児は心疾患, 供血児は腎疾患の症状を呈することがあり、重度の場合は子宮内胎児死亡に至ることもある。この疾患では、受血児側は羊水過多, 供血児は羊水過少になるため、胎児期の超音波検査により羊水量のバランスをみることで診断することが可能である。

この双胎間輸血症候群に対する治療としては、レーザ凝固術が行われている。この手術は、胎盤表面を走行する血管のうち、二児の血管が吻合している部分(供血児から受血児に血流が流れている部分)を特定し、レーザで凝固して止血することにより二児間の血流を遮断するものである。このとき、レーザは胎盤表面に対して垂直に照射しなければならない。しかし、内視鏡での限られたアプローチから任意の方向にレーザを照射することは極めて困難であり、特に胎盤が腹側に付着している場合は、母体の腹壁を切開し、子宮を取り出して内視鏡を挿入していた。

そこで、術具先端が自由に屈曲するレーザ搭載微細マニピュレータを提案する(Fig.1)。先端までは硬性にし、先端のみが屈曲することにより、術具全体を大きく動かす必要がなくなる。これにより、子宮の切開口付近や子宮内膜への損傷を抑えることができ、子宮刺激による早産のリスクを軽減することができる。また、アクチュエータを用いて先端を任意の角度に屈曲することにより、術者は自然な姿勢で術具を保持・操作することが可能となる。まずは早期の臨床応用を目的として、術者が手で持って操作するタイプのレーザ搭載微細マニピュレータを開発した。

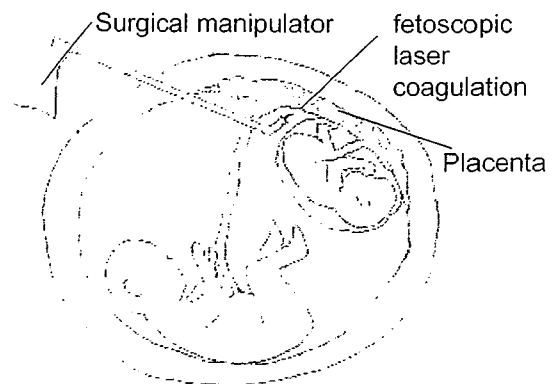


Fig.1 Laser therapy for Twin-Twin Transfusion Syndrome (TTTS)

2. レーザ搭載微細マニピュレータの仕様

低侵襲胎児手術を対象としたレーザ搭載微細マニピュレータとして、以下の仕様をみたす必要がある。

- 1)子宮にあける切開口、つまりトロカールを挿入する切開口が 3mm 以下であること。(切開口は小さいほど良い。切開口が大きい場合は羊水の漏れの危険があり、また子宮への刺激が大きいため早産のリスクが高まる。)
- 2)コア径 400 μm 、外径 700 μm のレーザファイバを挿入した状態でマニピュレータ先端が屈曲可能であること。
- 3)片手でマニピュレータの保持と先端の屈曲が操作できること。(もう一方の手ではトロカールを保持する。)

上記の仕様を満たす屈曲機構として、胎児手術用として開発しているボールジョイント型の屈曲機構⁴⁾(Fig.2)を用いたマニピュレータを試作した。この機構は、内部が中空になっており、さらに内径、つまり挿入するものの外径に対して、マニピュレータの外径が小さいという特徴を持つ。今回は、外径 2.4mm、内径 0.9mm の屈曲機構を製作した。この機構では、ジョイント数を4とした場合、内部にワイヤなどの柔軟なものを挿入した状態で、任意の方向に最大 180 度の屈曲が可能である。

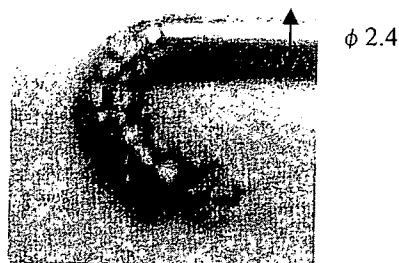


Fig.2 Bending mechanism with four ball joints

3. レーザファイバの搭載

まず、マニピュレータを片手で操作できるように、駆動部に手持ち部を設け、親指で押せる位置にスイッチを取り付けた(Fig.3)。スイッチは 4 つのスイッチを組み合わせたもので 8 方向の屈曲方向の指示が可能である。さらにこれに対して、コア径 400 μm 、外径 700 μm のレーザファイバを挿入し、屈曲動作を行った。

実験の結果、先端から 10mm の位置で約 50 度の屈曲を行うことができた(Fig.4)。また、レーザ出力への影響もなく、屈曲した状態で、かつ、羊水を模擬した水中で、鶏肉の表面をレーザで焼灼できることを確認した。

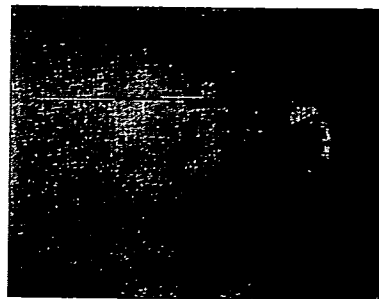


Fig.3 The tip of the fabricated prototype (bending position)



Fig.4 The tip of the fabricated prototype (bending position)

4. 考察とまとめ

双胎間輸血症候群に対して、更に低侵襲にレーザ凝固術を行うことができる可能性を示すことができた。実験で使用した屈曲機構は、屈曲部が約 8mm と短いため、屈曲半径が大きいレーザファイバに対して、十分な屈曲角度を得ることができなかった。これは、ジョイント数を増やし、屈曲部を長くすることで解決できると考える。

今後は、マニピュレータ内に、観察用ファイバと、治療用ファイバを複合させたファイバを挿入し、観察しながら治療を行うデバイスを開発する。また、胎盤表面との距離を適切に保ちながら、ターゲットに正確にレーザ照射が行えるよう、ナビゲーションシステムの開発とマニピュレータとの統合も進めていく。

文献

- 1) T.Chiba, M.R.Harrison, C.T.Albanese and D.L.Farmer, "Fetal Surgery: Past, Present, and Future", Fetal Surgery Japan Society of Prenatal and Neonatal Medicine, Vol.36, No.4, pp.524-539, 2000
- 2) 村越 毅, "多胎妊娠の管理-最近の知見疾病双胎の管理~双胎間輸血症候群の病態と治療~", 日本産科婦人科学会雑誌, Vol.55, N216-N223, 2003
- 3) Francois I.Luks, Stephen R.Carr, Monique E. Paepé, Thomas F. Tracy Jr, "What-and why- the pediatric surgeon should know about twin-twin transfusion syndrome", Journal of Pediatric Surgery, Vol40, pp1063-1069, 2005
- 4) 原田 香奈子, 坪内 広太, 千葉 敏雄, 藤江 正克, Open-MRI 下における低侵襲胎児手術用マニピュレータの開発, 第 13 回日本コンピュータ外科学会論文集, pp.111-112, 2004-12

直感的な作業進捗度・重要度理解のためのカラー等高線機能を備えた脳神経外科手術用ナビゲーションシステム

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Neuro-Navigation System with Color-mapped Contour for Intuitive Recognition of Task Progress and Value

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Abstract: Navigation system, which shows where surgeon is now on the screen of CT/MRI, contributes to safe, precise, and minimally invasive surgery. We have developed the Real-time Updating navigation system which combined intraoperative MRI and an optical navigation device for maximum removal of malignant brain tumor. On this research we focused on the problems; 1) it is difficult for surgeons to recognize the task progress and value of treatment shortly from rich information on medical images shown on the navigation system, 2) it is difficult for surgeons who concentrate to surgical field to see navigation window directly and carefully. We have developed the navigation system with intraoperative semi-automatic segmentation module for tumor. It helps surgeons with intuitive recognition of tumor region thorough navigation screen or sound information. In this paper, we report the development of novel navigation system with color-mapped counter inside of region of interest which helps surgeons with intuitive recognition of task progress and values.

Key words: Navigation system, Neurosurgery, Segmentation

1. はじめに

脳神経外科は CT、MRI の導入、顕微鏡手術の開発など 20 世紀に大きな発展を遂げた。術者が今どこにいるかを CT や MRI の画面上に示す技術—ナビゲーション—も 1990 年代に様々な方法が開発され、安全で低侵襲な手術に貢献している。我々は Open MRI による術中 MRI と、光学式ナビゲーション装置を組み合わせたリアルタイムアップデートナビゲーションシステムをベースに、脳腫瘍摘出術での腫瘍の最大摘出のための技術開発を行ってきた。¹⁾²⁾

本研究ではナビゲーションシステムにおける問題として、1) 作業進捗度や現在の作業ポイントの重要度という手術に必要な小要素を、ナビゲーション上に表示される医用画像(情報量大)から瞬時に獲得することが困難、2) 術者は術野に集中するため、ナビゲーション情報をリアルタイムに直接画面から視覚的に獲得することが困難、という点に着目している。我々はこれまでに腫瘍領域を術中に高速セグメンテーションし、腫瘍領域(関心領域)のみを直感的(視覚的・音により聴覚的)に確認することのできるナビゲーションシステムを開発している。³⁾本報ではさらに、関心領域を術者視線方向からの距離を用いて細分化し等高線的に表示することにより、術者に作業進捗度・重

要度の直感的かつ定量的な理解を提供する新しいナビゲーションシステムを開発したので報告する。

2. 方法

まず、腫瘍(関心領域)セグメンテーションデータを読み込み、画像空間と術野空間とのレジストレーションを行ったナビゲーションシステム上において、セグメンテーションされた腫瘍データ V_0 の輪郭面 S_0 状の各点 P_n と手術顕微鏡レンズ中央点 C とを結んだベクトル空間を計算により求める。次に各ベクトルを指定量 Δt だけ短縮し、ベクトル先端を結んだ面 $S_{\Delta t}$ を作成する。この 2 つの面で囲まれた領域 $V_{\Delta t}$ は、術者視線方向から考えて、腫瘍輪郭部からの距離が Δt 以下の領域となる(Fig.1)。 Δt を 5mm、10mm、20mm として計算した $V_{\Delta t}$ 群および V_0 とのそれぞれの差分をとることにより、輪郭からの距離 5mm 以下の領域、5mm 以上 10mm 以下の領域、10mm 以上 20mm 以下の領域、20mm 以上の領域のボリュームデータが作成される。これらをカラーマップしナビゲーション画像上に重畳することで、作業進捗度(あとどれくらい腫瘍が残っているか)および作業重要度(正常領域にどれくらい近いのか)を直感的かつ定量的に医師に提示することが可能となる。顕微鏡レンズ中央点 C の座標は反射球マーカールを取り付けた治具を作成しこれを顕微鏡に取り付け

ることにより行った(Fig.2)。

以上の方法により作成したカラー等高線作成機能を備えたナビゲーションシステムを、ファントム実験および臨床において試用し、その使用感及び有用性について定量的に評価した。(Fig.3、4)

3. 結果・

医師による試用の結果、従来のナビゲーションシステムでは得られない定量的な進捗・重要度の提示は有用であることが伺えた。2次元ディスプレイ上に表示される3次元医用画像データ上で定量的な3次元距離情報を獲得することは不可能に近く、この等高線表示機能によるわかりやすい定量情報の提示の有効性が示された。

また、関心領域の等方向的な拡大縮小により作成される等高線と異なり、顕微鏡視線方向からの等高線データを用いた方法では術者に近い側の腫瘍輪郭において高進捗度・高重要度を提示することがないため、腫瘍外側の一方から作業を行う脳腫瘍摘出術に適した方法であると考えられる。

一方、本手法では顕微鏡位置が変わるごとに等高線データの更新が必要となる。現在は手術時の安全性を考慮し顕微鏡(レンズ中央点)位置計測用治具を顕微鏡本体に据え付けておらず、位置が変わるごとに測定を行う必要があり、手術ルーチンにあわせた作業の検討及び据付の検討の必要性が認められた。

4. 結語

腫瘍領域を術者視線方向からの距離を用いて等高線的に表示することにより、術者に作業進捗度・重要度の

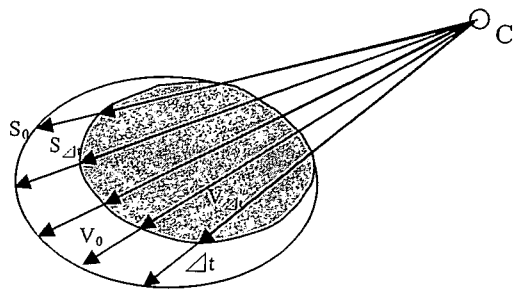


Fig.1 Color-mapped Contour generation using the distance between microscope and tumor contour.



Fig.2 Tool for measurement of center point of microscope lens

直感的かつ定量的な理解を提供する新しいナビゲーションシステムを開発し、臨床試用においてその有用性と運用上の検討事項を抽出した。今後臨床例を重ね、手術における有用性の評価と改良を加えていく。

謝辞

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文献

- 1) 杉浦円ほか、術中 MRI 下脳腫瘍摘出術における Updated-navigation システムの精度評価、日本コンピュータ外科学会誌 2005;7(1):43-49
- 2) N. Ozawa, et al: Navigation system based on intraoperative diffusion weighted imaging using open MRI, Proc of the 19th International Congress and Exhibition of Computer Assisted Radiology and Surgery CARS2005, H. U. Lemke, K. Inamura, K. Doi, M.W. Vannier & A.G. Farman (Editors). Springer, p810-814, 2005
- 3) Jae-Sung Hong, et al: Intraoperative 3-D Display of Tumor Resection Status based on the Trace of Surgical Device, the 6th Asian-Pacific Conference on Medical and Biological Engineering, Tsukuba, April 24-28, 2005, pp81,PA-3-89(CD), 2005

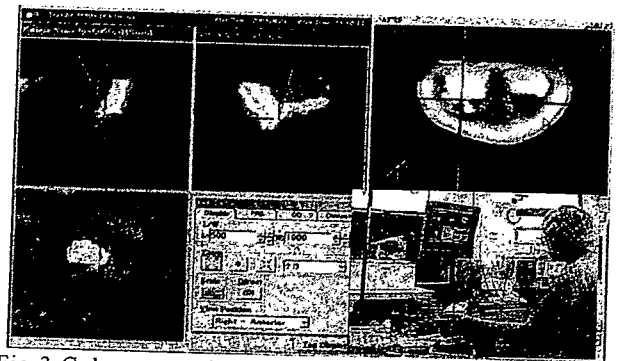


Fig.3 Color-mapped contour view on phantom test.



Fig.4 Clinical trial using color-mapped contour.

Manifestation of Mirror Syndrome after Fetoscopic Laser Photocoagulation in Severe Twin-Twin Transfusion Syndrome

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Key Words

Mirror syndrome · Hydrops fetalis · Twin-twin transfusion syndrome · Fetal treatment · Fetoscopic laser photocoagulation · Hyperreactio luteinalis

Abstract

Mirror syndrome is a preeclampsia-like disease first described in a case of severe hydrops fetalis caused by rhesus isoimmunization, later reported in some cases of nonimmunological fetal hydrops. Twin-twin transfusion syndrome (TTTS) is a severe complication associated with monochorionic pregnancies, in particular, severe TTTS with one hydropic fetus leading to a poor prognosis. We report here a case of mirror syndrome that occurred after selective fetoscopic laser photocoagulation in severe TTTS at 24 weeks' gestation.

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Introduction

Mirror syndrome was first described by John W. Ballantyne [1] in 1892, a syndrome in which a gravida patient essentially 'mirrors' the in utero state of the hydropic fetus. The outcome for mother and fetus is unfav-

orable without prompt delivery. The syndrome has been reported to be associated with Rh isoimmunization [2], nonimmune hydrops [3], placental chorioangioma [4], and various fetal anomalies [5, 6]. Twin-twin transfusion syndrome (TTTS) is a serious complication occurring in a monochorionic twin pregnancy that develops fetal hydrops. Fetoscopic laser photocoagulation of placental vascular anastomoses has been reported to be a promising therapy for severe TTTS in midgestation [7]. We report here the first case of mirror syndrome that was evident after selective fetoscopic laser photocoagulation in severe TTTS.

Case Report

A 33-year-old woman, gravida 2, para 2, at 24 + 5 weeks' gestation, was referred to our institution for management of TTTS. She had no history of infertility treatment. Ultrasound revealed polyhydramnios (maximum vertical pocket 15 cm) surrounding the recipient twin whose bladder was enlarged and oligohydramnios (maximum vertical pocket 1 cm) around the donor twin whose bladder was not visible. The discordance in estimated body weight between the two fetuses was 39%. Doppler studies of the recipient twin showed reverse flow in the ductus venosus and pulsatile umbilical venous flow without any signs of hydrops fetalis. A fetal echocardiogram of the recipient twin showed hypertrophic cardiomegaly with a cardiothoracic area ratio of 36%, moderate tricuspid

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regurgitation, and mild mitral valve regurgitation. Amnioreduction was performed twice within 3 days before the operation. The patient had slight pretibial edema, but no signs of hypertension or proteinuria were evident. Her laboratory data revealed normal renal and hepatic functions, although the hemoglobin and hematocrit values decreased sharply just before the operation (table 1). After approval of the Institutional Ethical Committee and after obtaining informed consent, selective fetoscopic laser photocoagulation of the placental vascular anastomoses was performed. An ultrasound examination just prior to the operation revealed hydrops fetalis with ascites, mild skin edema, and pericardial effusion in the recipient twin. Under general anesthesia using sevoflurane and continuous ultrasound visualization, a rigid 2-mm (diameter) 0°-fiber fetoscope (Karl Storz, Tuttlingen, Germany) housed in a 3-mm (diameter) cannula was inserted transabdominally into the amniotic cavity of the recipient twin. The communicating placental vessels were coagulated by an output of 30–40 W for 1–3 s with a 600- μ m (diameter) YAG laser fiber. The operation was completed

without any complications. After the operation, tocolysis was initiated by administration of an indomethacin (25 mg) suppository every 6 h for 24 h and maintenance of magnesium sulfate at a dose of 1.5 g/h. Thirty minutes after endotracheal extraction, the mother developed acute respiratory failure with dyspnea and an oxygen saturation <90%. The mother was immediately reintubated. A chest X-ray showed bilateral alveolar infiltration without cardiac enlargement, indicating the presence of pulmonary edema. Mechanical ventilation with positive end-expiratory pressure was started. The patient showed skin edema, oliguria, acute anemia, and hypoproteinemia (table 1).

On postoperative day (POD) 1, intrauterine death of the recipient twin and the donor twin with ascites were detected by ultrasound. On POD 2, the donor twin became hydropic with ascites, pericardial effusion, and scalp edema. She had 1+ proteinuria and slightly elevated liver enzyme levels (GOT 73 IU/l, GPT 42 IU/l). Administration of indomethacin was discontinued, and the dosage of magnesium sulfate was decreased. On POD 3 (25 + 4 weeks' gestation), the donor twin and the hydropic dead recipient fetus were suddenly delivered beyond control of uterine contraction. The male boy (weight 1,224 g, Apgar scores 1 at 1 min and 2 at 5 min) was immediately transferred to the neonatal intensive care unit. After delivery, maternal pulmonary edema gradually improved, and the patient was extubated on POD 6. Anemia, hypoproteinemia, proteinuria, and elevated liver enzyme levels also ameliorated (table 1). The placenta was edematous and large, weighing 830 g. Vascular anastomoses between the two fetuses and inflammatory signs were not detected on pathological examinations. The donor baby died due to severe acidemia and sepsis on the 10th day after delivery (POD 13). On POD 17, a CT examination of the mother was performed to exclude any other complications. The CT showed bilateral enlarged ovarian cysts, suggesting hyperreactio luteinalis (fig. 1). Bilateral ovarian cysts disappeared on POD 56, as evidenced by an ultrasound examination.

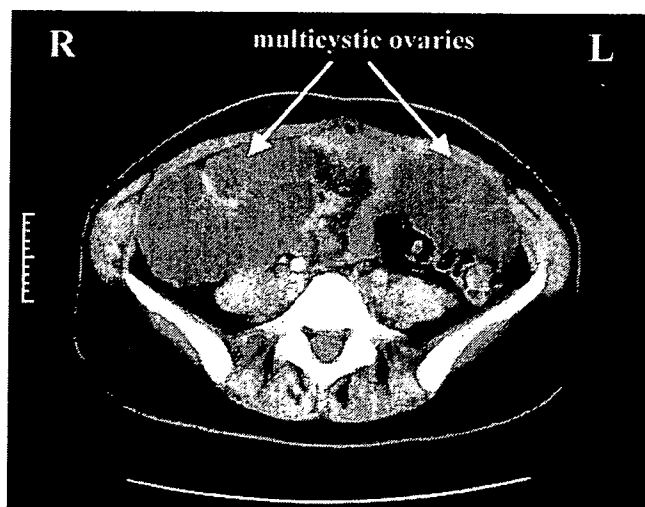


Fig. 1. CT on POD 17, showing enlarged bilateral multicystic ovaries.

Discussion

Maternal hydrops with lung edema and skin edema developed after fetoscopic laser photocoagulation and disappeared immediately after termination. Fetal hy-

Table 1. Summary of the laboratory data

	Gestational age					Post-partum day 1	Post-partum day 7
	24w5d (admission)	25w1d (before SFLP)	25w1d (after SFLP)	25w2d (recipient twin IUFD)	25w4d (donor twin delivery)		
Total protein, g/dl	6.3	5.2	4.3	4.4	4.9	5.3	6.4
Hemoglobin, g/dl	9.6	7.9	7.8	6.5	9.4	10.5	12.9
Hematocrit, %	26.8	22.1	22.3	18.5	26.9	29.4	36.3

SFLP = Selective fetoscopic laser photocoagulation; IUFD = intrauterine fetal death.

drops was observed in the recipient twin before the operation and in the donor twin afterwards. The placenta was large and hydropic. The mother exhibited the fetal state of hydrops associated with placental hydrops. This was a case of mirror syndrome in severe TTTS that was manifest after fetoscopic laser photocoagulation. To date, 21 cases of mirror syndrome have been reported [2–6, 8–18]. We presented the first case of mirror syndrome associated with severe TTTS.

Typical maternal symptoms include a rapid weight gain with marked lower-extremity edema, with some patients developing a preeclampsia-like syndrome. This case had lung and skin edemas, proteinuria, and elevated liver enzyme levels, but no evidence of hypertension was found. An important pathophysiological feature of mirror syndrome that distinguishes it from preeclampsia is maternal hemodilution which is clinically manifest as maternal anemia [8, 9]. On the contrary, preeclampsia and HELLP (hemolysis, elevated liver enzymes, and low platelet count) syndrome demonstrate hemoconcentration. In our case, hemoglobin and hematocrit values decreased dramatically before the operation, increased thereafter, and then recovered to normal after delivery. These laboratory data demonstrate that hemodilution, a hematological feature of mirror syndrome, had been observed before the operation.

It has been reported that maternal pulmonary edema after open fetal surgery is not rare [19]. The cause of pulmonary edema is not clear, although an association with tocolytics is suspected. Almost all cases of maternal pulmonary edema resolved rapidly without the need of intubation and positive pressure ventilation. A maternal pulmonary edema after endoscopic fetal surgery is less common and less severe than one after open fetal surgery [20]. Our other 13 cases of fetoscopic laser surgery for TTTS did not show any sign of pulmonary edema. This case showed preeclampsia-like symptoms with hemodilution. Taken together, this case is difficult to explain on the basis of a complication of endoscopic fetal surgery. An early state of mirror syndrome with hemodilution occurred before the operation, although the endoscopic fetal intervention may have influenced the manifestation of the mirror syndrome. It should be noted that the maternal condition may also be at risk, when fetal surgical intervention is considered due to fetal hydrops.

Although the precise pathophysiology of mirror syndrome is unknown at present, some reports suggest that there is a real connection between the fetal and the maternal manifestations. The prognosis of mirror syndrome is usually poor without prompt termination of the preg-

nancy. Pirhonen and Hartgill [18] reported a case of mirror syndrome in a dichorionic twin pregnancy, in which maternal edema resolved after the death of one hydropic twin. Another dichorionic twin pregnancy resulted in resolution of maternal mirror syndrome after selective termination of one hydropic fetus at 16 weeks' gestation [10]. In our case, one hydropic fetus died after fetoscopic surgery, and the other fetus was subsequently delivered due to uncontrolled uterine contractions. Although our case was a monochorionic twin, it is possible that maternal edema might improve after the death of the hydropic fetus, if preterm labor could be managed.

Interestingly, the CT examination on POD 17 in our case revealed bilateral ovarian cysts, suggesting hyperreactio luteinalis, and ultrasonography on POD 56 showed normalized ovaries. This case was a spontaneous twin pregnancy with no history of ovarian hyperstimulation syndrome at early gestation. Although the level of human chorionic gonadotropin (HCG) was not examined, hyperreactio luteinalis occurs more commonly in states associated with very high HCG concentrations, such as gestational trophoblastic disease [21]. Elevated levels of HCG may be associated with mirror syndrome, as suggested by the observation of a case with placental chorioangioma, in whom mirror syndrome was present [22]. Our case had hyperreactio luteinalis, also suggesting a link between HCG and etiology of mirror syndrome.

References

- 1 Ballantyne JW: The Disease and Deformities of the Foetus. Edinburgh, Oliver & Boyd, 1892.
- ▶ 2 Kaiser IH: Ballantyne and triple edema. *Am J Obstet Gynecol* 1971;110:115-120.
- ▶ 3 John AH, Duncan AS: The maternal syndrome associated with hydrops foetalis. *J Obstet Gynaecol Br Commonw* 1964;71:61-65.
- ▶ 4 Dorman SL, Cardwell MS: Ballantyne syndrome caused by a large placental chorioangioma. *Am J Obstet Gynecol* 1995;173:1632-1633.
- ▶ 5 Carbillon L, Oury JF, Guérin JM, Azancot A, Blot P: Clinical biological features of Ballantyne syndrome and the role of placental hydrops. *Obstet Gynecol Surv* 1997;52:310-314.
- ▶ 6 Ordorica SA, Marks F, Frieden FJ, Hoskins IA, Young BK: Aneurysm of the vein of Galen: A new cause for Ballantyne syndrome. *Am J Obstet Gynecol* 1990;162:1166-1167.
- ▶ 7 Senat MV, Deprest J, Boulvain M, Paupe A, Winer N, Ville Y: Endoscopic laser surgery versus serial amnioreduction for severe twin-twin transfusion syndrome. *N Engl J Med* 2004;351:136-144.
- ▶ 8 van Selm M, Kanhai HH, Gravenhorst JB: Maternal hydrops syndrome: A review. *Obstet Gynecol Surv* 1991;46:785-788.
- ▶ 9 Hirsch MR, Mark MS: Pseudotoxemia and erythroblastosis: Report of a case. *Obstet Gynecol* 1964;24:47-48.
- ▶ 10 Hcyborne KD, Chism DM: Reversal of Ballantyne syndrome by selective second-trimester fetal termination: A case report. *J Reprod Med* 2000;45:360-362.
- ▶ 11 Midgley DY, Harding K: The mirror syndrome. *Eur J Obstet Gynecol Reprod Biol* 2000;88:201-202.
- ▶ 12 Nicolay KS, Gainty HL: Pseudotoxemic state associated with severe Rh Isoimmunization. *Am J Obstet Gynecol* 1964;89:41-45.
- ▶ 13 Cohen A: Maternal syndrome in Rh iso-immunization: report of a case. *J Obstet Gynaecol Br Emp* 1960;67:325-327.
- ▶ 14 Keane B: Maternal syndrome associated with hydrops foetalis: Case report. *NZ Med J* 1978;88:56-57.
- ▶ 15 Quagliarello JR, Passalacqua AM, Greco MA, Zinberg S, Young BK: Ballantyne's triple edema syndrome: Prenatal diagnosis with ultrasound and maternal renal biopsy findings. *Am J Obstet Gynecol* 1978;132:580-581.
- ▶ 16 Sydorak RM, Kelly T, Feldstein VA, Sandberg PL, Silverman NH, Harrison MR, Albanese CT: Prenatal resection of a fetal pericardial teratoma. *Fetal Diagn Ther* 2002;17:281-285.
- ▶ 17 Vidaeff AC, Pschirrer ER, Mastrobattista JM, Gilstrap LC 3rd, Ramin SM: Mirror syndrome: A case report. *J Reprod Med* 2002;47:770-774.
- ▶ 18 Pirhonen JP, Hartgill TW: Spontaneous reversal of mirror syndrome in a twin pregnancy after a single fetal death. *Eur J Obstet Gynecol Reprod Biol* 2004;116:106-107.
- ▶ 19 DiFederico EM, Burlingame JM, Kilpatrick SJ, Harrison M, Matthey MA: Pulmonary edema in obstetric patients is rapidly resolved except in the presence of infection or of nitroglycerin tocolysis after open fetal surgery. *Am J Obstet Gynecol* 1998;179:925-933.
- ▶ 20 Harrison MR, Sydorak RM, Farrell JA, Kitterman JA, Filly RA, Albanese CT: Fetoscopic temporary tracheal occlusion for congenital diaphragmatic hernia: Prelude to a randomized, controlled trial. *J Pediatr Surg* 2003;38:1012-1020.
- ▶ 21 Santos-Ramos R, Fomey JP, Schwarz BE: Sonographic findings and clinical correlations in molar pregnancy. *Obstet Gynecol* 1980;56:186-192.
- ▶ 22 Gherman RB, Incerpi MH, Wing DA, Goodwin TM: Ballantyne syndrome: Is placental ischemia the etiology? *J Matern Fetal Med* 1998;7:227-229.

Bending Laser Manipulator for Intrauterine Surgery

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Abstract—A bending laser manipulator has been developed for intrauterine surgery; twin-twin transfusion syndrome (TTTS). TTTS is a condition seen in 10-15% of monochorionic diamniotic twins (a single placenta, separate amniotic sacs) and causes blood volume unbalance between both babies through communicating vessels in the placenta. Although the laser coagulation of communicating vessels in the placenta is effective treatment for TTTS, precise maneuvering of the laser's tip through one small port in both abdominal and uterine walls is very difficult. In this paper, a bending laser manipulator of diameter 2.4mm has been proposed to perform the surgery with high dexterity. The manipulator has a laser fiber inside of it and bends through 60 degrees in any direction. Simple handheld interface has been chosen for early clinical use. This manipulator enables minimally invasive intrauterine surgery even when the mother has the anterior placenta and the choices of access path are quite limited.

Keywords – *surgical robot, fetal surgery, intrauterine surgery, minimally invasive surgery, TTTS*

I. INTRODUCTION

Over the last decades, developments of surgical robots have considerably progressed, with some commercially available and clinically applied for many cases around the world described in many papers for example [1, 2]. The development of surgical robots has contributed to a widespread rise in the use of minimally invasive surgery, resulting not only decreased patient pain but also reduced medical costs due to a shorter stay required in hospital.

In this paper, the clinical target of this study is intrauterine fetal surgery. The fetal surgery is a relatively new procedure, with only hundreds operations around world, because of the risk of premature delivery caused by the stimulation on the uterine and fetus [3-5]. To perform minimally invasive fetal surgery, that is intrauterine surgery, high dexterous surgical robot would be useful. In this research, the specifications for the minimally invasive technique are analyzed then a bending laser manipulator is developed as a high dexterous tool.

This paper is organized as follows. The next sections review the background to minimally invasive fetal surgery. Following the proposed concept and procedure of

intrauterine surgery are described, and the design of the bending laser manipulator and its prototype are presented. Finally the future works are discussed.

II. COMPUTER AIDED FETAL SURGERY

A. Minimally invasive fetal surgery

Fetal surgery has recently progressed because ultrasonic imaging technique and genetic diagnosis lead to an increased detection of fetal problems in the early stages of the gestation. Fetal intervention has been performed in the manner of open surgery or fetoscopic surgery. In open surgery, surgeons have clear view and high dexterity for surgical manipulation but large incision in uterus often causes preterm delivery. On the other hand, fetoscopic surgery was developed in 1980's to minimize the incision in uterus. This surgery can be done through small hole in mother's abdominal wall (percutaneous) or through small opening in the abdominal wall. This surgery is better for mother than open surgery but it has technical problems and needs new devices to perform delicate work through small holes in the uterus. The effect differences in surgical procedures are still under study such as described in [6-11].

The difficulties of the fetal surgery compared with other forms of surgery are the following:

1) The fetus in the target gestation is very small (the weight of 250-650g) and fragile. It is floating in amniotic fluid in the uterine with unstable position and posture.

2) Insertion sites for surgical instruments into the uterine depend on the position of the placenta (anterior placenta or posterior placenta) and the allowable space for instruments within the uterus is limited.

3) The fetoscopic view is unclear due to the cloudy nature of the amniotic fluid.

4) The performance of common surgical instruments, such as an electric scalpel, is limited when they are used in amniotic fluid.

5) Damage to a uterus, a placenta and a fetus could cause premature delivery.

6) A flaccid uterus and placenta under anesthesia is always at risk of massive bleeding.

7) The mother under surgical operation is also at risk of infection and a lost next chance of pregnancy.

B. Robotic approach for fetal surgery

Some researchers have studied the feasibilities of using robotic procedures for fetal surgery, using animal fetuses such as sheep[12-13]. They used commercially available surgical robot to test whether it is useful for spina bifida treatment where the back of a fetus is need sutured. The result showed the robotic approach for intrauterine fetal surgery has many technical problems to overcome.

The diameter of commercially available surgical manipulators is too big for the target size and surgical space allowable. The bigger incisions in the uterus for tool insertion are more invasive than the incisions for usual tools for manual operation. The long setup time for a robotic operation was also time-consuming and the advantages of surgical results were not demonstrated in comparison to the manual operative approach.

Our motivation is to overcome the aforementioned problems and propose new procedure allowing robotic fetal surgery in a minimally invasive manner.

III. PROPOSED ROBOTIC SURGERY

A. Surgical Target

Fetoscopic surgery is often performed for twin-twin transfusion syndrome (TTTS). TTTS is an abnormal condition seen in 10-15% of monochorionic diamniotic twins. The twins share single placenta and have separate amniotic sacs. In TTTS, babies have communicating vessels in the placenta and abnormal blood flows one baby (donor) to the other (recipient) as shown in Fig.1. The donor has less blood supply to its internal organs such as kidneys resulting in its small amniotic fluid volume. On the other hand, the recipient with too much blood supply has a large amniotic fluid volume and can have heart failure or soft tissue swelling. Without treatment for severe TTTS, twins will die or have brain damage.

The common treatment for TTTS is amnioreduction where large volumes of amniotic fluid are drained with a needle inserted into the sac of the recipient twin. This increases survival rates, however, some cases do not respond to this treatment. These cases are treated by laser coagulation of connecting vessels in the placenta. The laser fiber is inserted together with a fetoscope through the mother's abdomen and the uterus. Then laser coagulation is performed at vessels' connecting points in the placenta.

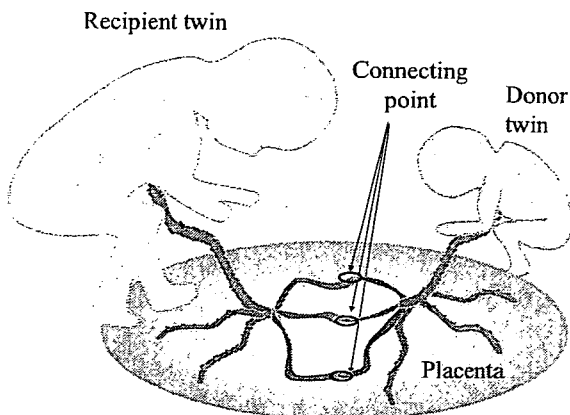


Fig.1 Twin-twin transfusion syndrome(TTTS)

B. Proposed Robotic Surgery for TTTS

When the placenta is attached to the front side of the uterus (called "anterior placenta"), which is seen about 40% of whole pregnancy, the mother's abdominal wall is widely open to make an access port from the back side of the uterine wall avoiding placental injury. The uterus is exposed and rotated during the operation.

To avoid this large incision on the mother's abdominal wall, we propose a bending laser manipulator. A bending manipulator has two DOF joint at the tip and an optic fiber is inserted through the manipulator. The diameter of incision in the uterus for the manipulator's insertion must be less than 3mm. When the outer diameter of the inserted tool is less than 3mm, the hole in the uterus need not sutured, since the contractive force of the uterus itself closes the small hole unaided. Of course, it is better both for the mother and babies that the incision in abdominal and uterine wall is as small as possible. The larger hole in the uterus needs sutured, which may result in a leak of amniotic fluid and severe pain to the mother.

The following surgical procedures are proposed for the minimally invasive robotic surgery for TTTS. Fig.2 shows surgical concept with the proposed bending laser manipulator.

- 1) Control the amount of amniotic fluid to make appropriate surgical space if necessary. When the turbidity of the amniotic fluid is high, it is replaced with warmed saline water to have a clear view inside the uterus.
- 2) Place a 3D ultrasonic probe on the mother's abdominal wall to decide the position and direction of the instruments' insertion (A tool navigation system with 3D ultrasound real time data is being developed).
- 3) Insert a bending laser manipulator into amniotic sac of the recipient twin to penetrate both the abdominal and uterine walls at the same time under ultrasonic monitoring. Quick insertion is necessary since slow access into uterus could cause the amniotic membrane to peel off from the uterine wall and lead to premature delivery.
- 4) Examine the surface of the placenta carefully to determine the abnormal vascular connections between the twins among many vessels in the placenta. The connecting vessels are in the territory between the twins and crossing the dividing membrane.
- 5) Direct a laser beam selectively at the determined connecting vessels to eliminate their blood flow. The laser tip must be placed as vertically as possible to the placental surface in the aspect of its effectiveness.

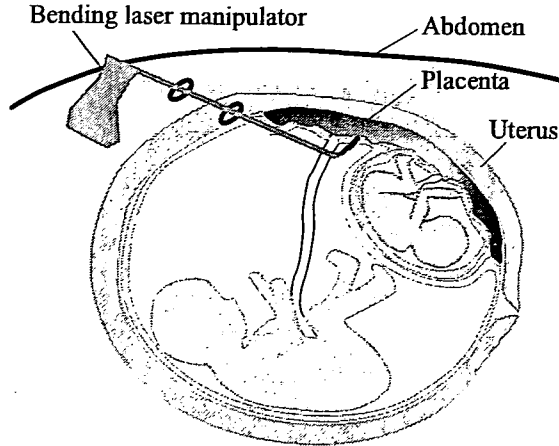


Fig.2 Concept for the proposed robotic surgery

IV. BENDING LASER MANIPULATOR

A. Bending Mechanism

The Fig.3 represents the design of the bending mechanism. The mechanism of the manipulator includes ball joints and they are driven using four wires (each of diameter is 0.27mm) enable a bend of 90 degrees in any direction when it has two joints. The diameter is 2.4mm and the bending radius is 2.45 mm. The manipulator includes an inner hole through all ball joints, making it easy to develop many types of surgical applications. The features of this mechanism include small diameter and bending radius, ease of fabrication, and high rigidity compared with other bending mechanism for example[14-16], and low cost for manufacturing. The designed bending angle and bending length are easily changed just with changing the assembly procedures.

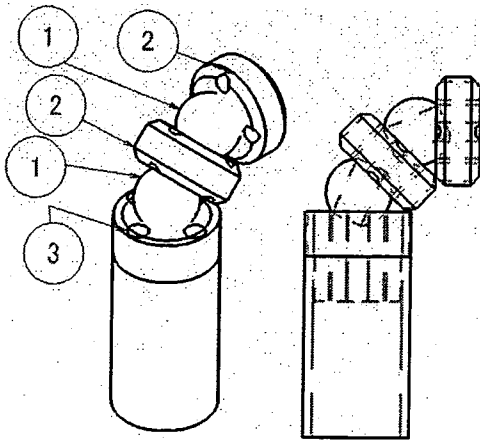


Fig.3 New design of the mechanism

(In Fig3, No.1: ball with a through-hole, No.2: parts of the bending mechanism, No.3: a part inserted into a pipe. All of them have four holes for the wire path. Nos.2 and .3 are made of Titanium)

The relation of the wire pull length and bending angle are shown in the Fig.4.

The following symbols are defined:

- t- wire pull length for each joint
- t_1 -maximum distance between two joint parts
- t_2 -minimum distance between contact lines of a ball and a joint part
- t_3 - wire length between two joint parts
- R- distance from the center of a ball to a guide hole for each wire
- θ - angle of each bending joint
- O- center of the ball
- a- distance between the center axis of the joint and the contact line of a ball and a joint part
- b- distance between the center axis of the joint and a guide hole for each wire

The relation of wire pull length and bending angle is described in Eq.(1)-(4);

$$t_1 = 2(R^2 - a^2)^{1/2} \quad (1)$$

$$t_2 = t_1 \cos(\theta/2) - 2a \sin(\theta/2) \quad (2)$$

$$t_3 = t_2 - 2(b-a) \sin(\theta/2) \quad (3)$$

$$t = t_1 - t_3$$

$$= t_1 - t_1 \cos(\theta/2) + 2a \sin(\theta/2) + 2(b-a) \sin(\theta/2)$$

$$= 2(R^2 - a^2)^{1/2}(1 - \cos(\theta/2)) + 2b \sin(\theta/2) \quad (4)$$

When the joint number is defined as N, the total bending Θ is described in Eq.(5);

$$T = 2N(R^2 - a^2)^{1/2}(1 - \cos(\Theta/2N)) + 2b \sin(\Theta/2N) \quad (5)$$

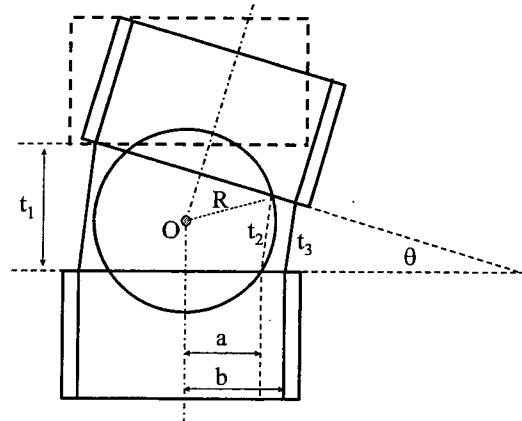


Fig.4 Relation of the wire pull length and bending angle

In this paper, a bending manipulator with four joints is fabricated as shown in Fig.5. The joint parts are made of

Titanium so that this can be used for the surgeries in Open-MRI in the future.

A wire is inserted through the center holes of all joints to make the each joint angle equal. This manipulator is confirmed to bend through 180 degrees in any direction. When the Eq(5) is applied, the total wire pull length to bend 180 degree is 3.03 mm.

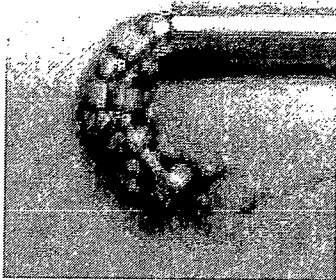


Fig.5 Bending mechanism with four ball joints

B. Control Unit

A driving unit with two ultrasonic motors is fabricated using a photo molding machine. One motor is used for each pair of the wires since the bending mechanism is symmetrical, which means that wire pull length and wire release length for a pair of wires are same.

The interface to a surgeon was designed as handheld type (Fig.6). The bending angle is indicated using a quadrant switch equipped with four switches. The manipulator is hold with a hand and the switch is pressed with the thumb.

The ultrasonic motors are controlled using PC104 and real time operation system QNX (QNX software systems, Canada) (Fig.7).

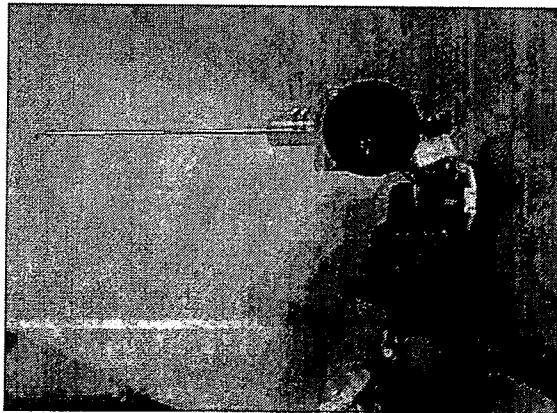


Fig.6 The tip of the fabricated prototype (bending position)

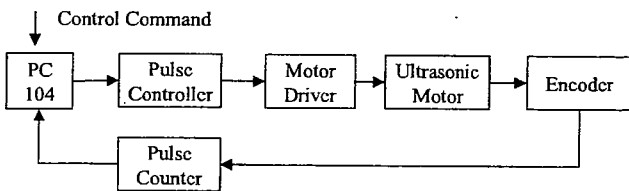


Fig7 Motor Control system

C. Bending test with a laser fiber inside the bending manipulator

A laser fiber whose core diameter is 0.4mm and outer diameter is 0.7mm was inserted through the center holes of all joints of the bending manipulator (Fig.8). With the fiber inside, the maximum bending angle was 60 degrees in any direction. This is because the fiber's stiffness is high and curvature radius is big to bend within the short length of 10mm as designed. Some joints will be added to bend up to 90 degrees in any direction. On the other hand, the bending angle for each joint was uniform due to the stiffness of the fiber. This means precise controllability for positioning its tip.

Fig.9 shows the result of an experiment on positioning accuracy to bend through 20 degrees. The test was repeated five times. Despite of the hysteresis, the minimum variation was kept less than three degrees. This is small enough for changing the angle with the hand-held switch. The monitored hysteresis is due to the initial condition of wire tensioning and small gaps between the mechanical parts and the laser fiber. The mechanical improvement and control algorithm is future work for more precise positioning and integration the manipulator to 3D ultrasound navigation system.

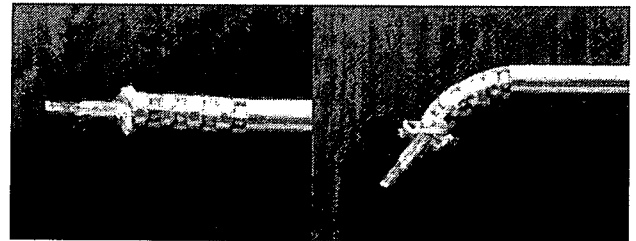


Fig8 Laser bending manipulator

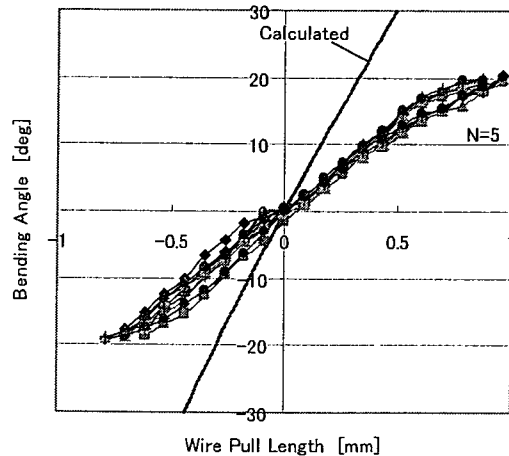


Fig9 Positioning accuracy of the bending laser manipulator

D. Laser coagulation test

Nd:YAG laser coagulation test was performed with a laser unit (6100-B, Dornier MedTech, Germany). The target of the test was blood vessels in a flesh mesenterium of a rabbit. The laser output was set at 50 W and the laser beam was irradiated for one second for each target spot. The laser tip was placed at 10mm away from the target surface. The result of the test is shown in Fig.10 where the two

coagulated vessels with the bended laser fiber are confirmed.

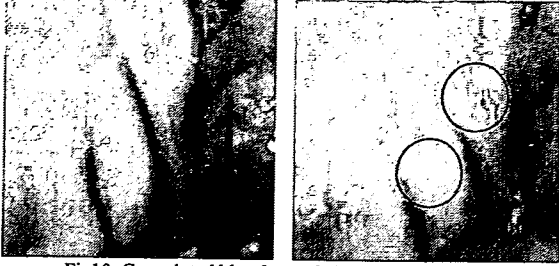


Fig10 Coagulated blood vessels in rabbit's mesentery

V. DISCUSSION AND FUTURE WORK

The advantage of the developed bending mechanism is very small diameter which can satisfy the specifications for intrauterine surgery, while the disadvantage is that its positioning control is influenced by the material inserted into the manipulator. The precise position control algorithm with the model of an inserted tool will be developed in the future.

The handheld interface is in good repute for surgeons. Although many researchers have studied master-slave type surgical robotic system, we have tried a simple and inexpensive surgical manipulator. Our approach is to develop a simple surgical manipulator as the first step and prove that high dexterous robotic tool is useful and can be easily introduced to clinical cases.

VI. CONCLUSION

A bending laser manipulator of diameter 2.4mm has been developed for intrauterine surgery. Its maximum bending angle is 60 degrees in any direction.

Although the manipulator has some technical problems to overcome, the demonstrated result put the intrauterine robotic surgery into possible reality. This manipulator will be applied not only TTTS therapy but other kinds of intrauterine fetal surgery. We believe that surgical robotic technologies would lead to the major break through to conquer the severe difficulty in fetal surgery.

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REFERENCES

- [1] Deon F. Louw, M.D., et al., "SURGICAL ROBOTICS: A REVIEW AND NEUROSURGICAL PROTOTYPE DEVELOPMENT", *Neurosurgery*, Vol54, No.3, March 2004.
- [2] Kevin Cleary, Charles Nguyen, "State of the Art in Surgical Robotics: Clinical Applications and Technology Challenges", *Computer Aided Surgery*, November 2001.
- [3] Michael R. Harrison, et al., *The Unborn Patient: The Art and Science of Fetal Therapy*, Elsevier Science Health Science div, 2001.
- [4] Michael R. Harrison, *The Unborn Patient: Prenatal Diagnosis and Treatment*, Elsevier Science Health Science div, 1991.
- [5] T.Chiba, M.R.Harrison, C.T.Albanese and D.L.Farmer, "Fetal Surgery: Past, Present, and Future", *Fetal Surgery Japan Society of Prenatal and Neonatal Medicine*, Vol.36, No.4, pp.524-539, 2000
- [6] N.Tulipan, "Intrauterine closure of myelomeningocele: an update", *Neurosurgery Focus*, Vol.16, pp1-4, February, 2004
- [7] J.P.Bruncr, N.B.Tulipan, W.O.Richards, W.F.Walsh, F.H.Boehm and E.K.Vrabcak, "In utero Repair of Myelomeningocele: A Comparison of Endoscopy and Hysterotomy", *Fetal Diagnosis and Therapy*, Vol15, pp.83-88, 2000
- [8] Daniellc S. Walsh, N. Scott Adzick, "Foctal surgery for spina bifida", *Seminars in Neonatology*, (2003)8, pp197-205.
- [9] Mark P. Johnson, MD, et al., "Fetal myelomeningocele repair: Short-term clinical outcomes", *Am J Obstet Gynecol*, August 2003.
- [10] Joseph P Bruncr, et al., "Intrauterine repair of spina bifida: Preoperative predictors of shunt-dependent hydrocephalus", *American Journal of Obstetrics and Gynecology*, (2004) 190, pp1305-12.
- [11] Joseph P Bruncr, William O. Richards, Noel B. Tulipan, Timothy L. Arncy, "Endoscopic coverage of fetal myelomeningocele in utero", *Am J Obstet Gynecol*, January 1999.
- [12] Oran S. Aaronson, Noel B. Tulipan, Robert Cywes, Hakan W. Sundell, Georges H. Davis, Joseph P. Bruncr, William O. Richards, "Robot-Assisted Endoscopic Intrauterine Myelomeningocele Repair: A Feasibility Study", *Pediatric Neurosurgery*, 2002 36: pp85-89.
- [13] T. Kohl, et al., "Percutaneous fetoscopic patch coverage of experimental lumbosacral full-thickness skin lesions in sheep", *Surgical Endoscopy* (2003) 17 :pp1218-1223.
- [14] Nakamura R, Oura T, Kobayashi E, Sakuma I, Dohi T, Yahagi N, Tsuji T, Shimada M, Hashizume M " Multi-DOF Forceps Manipulator System for Laparoscopic Surgery - Mechanism miniaturized & Evaluation of New Interface ", *Proc of Fourth International Conference on Medical Image Computing and Computer assisted Interventions(MICCAI2001)*, Utrecht, the Netherlands, October 14-17, 2001: pp.606-613, 2001.
- [15] Kouji Nishizawa, Kousuke Kishi, "Development of Interference-Free Wire-Driven Joint Mechanism for Surgical Manipulator Systems", *Journal of Robotics and Mechatronics*, Vol.16, No.2, 2004.
- [16] Y. Haga, M. Esashi, "Biomedical Microsystems for Minimally Invasive Diagnosis and Treatment", *IEEE Proceedings of the IEEE*, 92(1), (2004), pp98-114.

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胎児胸水の管理と治療

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はじめに

胎児胸水 (fetal hydrothorax, fetal pleural effusion/fetal PE) の頻度は概して高いものではなく、その原因はさまざまである¹⁾。しかし、本症において最も問題となる点は、この PE が物理的ないし病態生理学的に胸腔内腫瘍性病変と類似した挙措をとるということである。すなわち、胎児においても胸壁組織のコンプライアンスは低いことから、胎児 PE という胸腔内 space occupying lesion の存在は、胸壁自身の形成・発達というよりも、胸腔内臓器の発達・機能に負の影響を及ぼすということである。その結果、循環障害 (心不全)・胎児水腫 (fetal hydrops ; 時に placentomegaly を伴う)、肺低形成 (pulmonary hypoplasia) が児の予後という観点からは最も重要な問題となる。同時に、羊水過多症 (polyhydramnios) 合併などによる早産・未熟児分娩も、周産期死亡の主要な原因となっている。さらに、胎児 PE 発症の背景にある染色体異常 (aneuploidy)、子宮内感染症なども予後不良因子となる。したがって、(その原因にもよるが) 全体として PE を発症した胎児の周産期死亡率は、(特に早期発症例では) 50%を超えたとする報告もみられる。

このような状況は、イメージのうえで出生後にみられる PE とは大きく異なるものである。本稿では、PE を発症した胎児の病態とその胎

児期・周産期管理につき述べてみたい。

胎児 PE の疫学

胎児 PE は、いわゆる isolated のものと胎児水腫徴候の一部として認められるものとに分けられる。またその成因から一般には、primary と 2ndry のものと分けられる。ここで前者は、いわゆる “lymphatic malformation”，すなわち (fetal) chylothorax であり、外科的子宮内治療 (後述) が考慮される病態の主体をなす (その成因にはリンパ液の過剰産生、漏出、吸収障害などの関与も想定される)。これに対し後者は、通常は合併異常 (胎児心奇形・不整脈、貧血、肝/代謝障害、CCAM・肺分画症、横隔膜ヘルニア、胎盤/臍帯の形態異常、感染症、染色体異常 aneuploidy 等) に伴うもので、きわめてまれながら、先天性横隔膜ヘルニア/肺の先天性リンパ管拡張症 (congenital pulmonary lymphangiectasia) に合併した胎児 PE 症例も報告されている²⁾。Primary PE の頻度は約 12,000 ~ 15,000 妊娠に 1 例とされるが、今後胎児診断のいっそうの進歩に伴い、その発症率はより高いものとなってくるであろう。本 PE は、従来一般に男児に多く (male/female = 2)、片側性 (右側優位) 症例の頻度が高いとされ、高度例では everted diaphragm を呈することもある。新生児期以降の chylothorax の診断は、PE の性状 (乳び成