害を来していないことからこの点は明かである．しかし，術前ＣＴで形態学的に同定されたいわゆるＡ動脈が本当に血行動態的にも再建を要するか否かについては，従来判断する方法がなかった．冷却血液負荷ＭＥＰはそれを可能にする可能性が示唆されている．

E. 結論

術前ＣＴによる脊髄灌流動脈のスクリーニングと術中冷却血液負荷ＭＥＰは効率的に大動脈再建を行う上で有用である．

F. 健康危険情報：特記すべきものなし

G. 研究発表

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H. 知的財産権の出願・登録状況（予定を含む）

1. 特許取得：該当なし
2. 実用新案登録：該当なし
3. その他

厚生労働科学研究補助金（循環器疾患等生活習慣病対策総合研究事業）
分担研究報告書

髄障害防止の観点からみた胸部下行・胸腹部大動脈瘤外科治療ないしは ステントグラフト治療体系の確立に関する研究

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研究要旨
胸部下行大動脈瘤・胸腹部大動脈瘤の治療（手術およびステントグラフト）において、術前のMRIやCTによるAdamkiewicz動脈の同定実施が治療後の脊髄障害発生に与える影響について検討する。さらに胸部下行・胸腹部大動脈瘤手術およびステントグラフト治療における脊髄障害発生に与える要因全体を検討する。

A. 研究目的

本研究の目的は、胸部下行・胸腹部大動脈手術において、術前のMRIやCTによるAdamkiewicz動脈の同定実施が脊髄障害発生に与える影響(発生防止のための有効性)について検討する。さらに、胸部下行・胸腹部大動脈手術およびステントグラフト治療における脊髄障害発生に与える要因を検討することにより、脊髄障害発生率の軽減、治療成績の向上を目的とする。

B. 研究方法

1)胸部下行・胸腹部大動脈手術もしくはステントグラフト治療を施行される患者において、CTもしくはMRIによるAdamkiewicz動脈の同定実施が脊髄障害発生に与える影響を多施設共同コホート研究(前向きおよび後ろ向き)にて検討する。

2) 胸部下行･胸腹部大動脈手術もしくはステントグラフト治療を施行される患者において、脊髄障害および院内死亡の発生に影響を与える要因について多施設共同コホート研究(前向き)にて検討する。

3)Adamkiewicz 動脈の同定に関して、部位、同定可能割合について多施設共同コホート研究(前向きおよび後ろ向き)にて調査する。

胸部下行､胸腹部大動脈瘤に対する手術を必要とする患者のうち、選択基準をすべて満たし、かつ除外基準のすべてに抵触しない全ての患者を対象とする。

【選択基準】

1. 胸部下行、胸腹部大動脈手術もしくはステントグラフト治療を施行された患者
2. 2000年1月から2010年12月までに手術を施行された患者
3. 前向き登録を行う患者に対しては、同意能力があり、自ら同意文書に署名できる患者

方法： 研究デザイン

多施設共同コホート研究である。

今年度までに過去の後ろ向き研究のデータ収集は終了した。

（倫理面への配慮）

医学研究及び医療行為の対象となる個人の人権の擁護：本研究は患者を対象とした多施設共同の臨床研究であり､ヘルシンキ宣言及び臨床研究に関する倫理指針､特に疫学研究の指針を遵守して実施する。

Adamkiewicz 動脈の同 定の実施の利益、不利益を十分説明して同意を得る。治療に関しては現行の治療の枠 を越えるものではないため、患者側の不利益は生じないと考えるが、検査が増加する可能 性があり、検査の内容、意義を説明し同意を得る。本研究を開始する前に、申請者の施設の倫理委員会において十分検討審査を受けた後、研究を開始する。本研究で得ら れた個人情報は画像情報も含め厳重に保護し、個人を特定できる情報は開示しないなど取 り扱いには十分留意する。本研究は研究対象者の自発的同意と協力により行い、いず れの段階でも同意を撤回拒否でき、拒否による不利益はないものとする。

C. 研究結果

これまでの過去の症例においては6年前より MDCT による Adamkiewicz 動脈 の同定は 90%症例で可能であった。当科の症例においては、ステントグラフト症例では3%の脊髄障害例が あったが、これは全て不全対麻痺であった。胸部下行と胸腹部の手術症例においては術後生存例に おいては不全対麻痺の発生が 1 例のみで 3%の発生率、おそらく Adamkiewicz 動脈の同定は効果的 であったと思われる。しかし、過去の症例において、40 例の open stent 法を用いた弓部置換手術で 3 例の不全対麻痺を認めた。それ以外の弓部置換手術 120 例で 2 例の不全対麻痺が認められた。

D. 考察

ステントグラフト症例での不全対麻痺は左鎖骨下動脈と腹部大動脈の腰動脈の 影響があるものと考えられ、これらが脊髄障害発生の要因となる可能性が考え られた。手術症例においては大動脈遮断時間、体温、遮断範囲などの要因もあ り、検討要因項目の今後の選択にも注意を要する。弓部置換手術での不全対麻痺は解離の症例で、下行の解離腔閉鎖が不全対麻痺の発症に関与したものと考えられた。Open stent の症例ではステントグラフト挿入範囲は広範囲でなく、下行大動脈の粥腫を認める症例に発症し、微少塞栓症の関与も示唆された。

E. 結論

現時点での結論は困難であるが、手術およびステントグラフトでの治療にさい して Adamkiewicz 動脈の同定が成績向上（対麻痺発生の予防）に貢献している のではないかと思われるが、現在までに発症した脊髄虚血症例は多くが不全対麻痺であり、原因としては脊髄全体の相対的虚血と微小塞栓症が考えられ、さらなる症例の追加および血管壁の粥腫の状態や開存する肋間動脈、腰動脈の検索が必要ではないかと考える。今後更なる症例の追加が必要である。

F. 健康危険情報

不全対麻痺発症症例は全例が歩行可能となり、重度の後遺症は残さなかった。

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H. 知的財産権の出願・登録状況（予定を含む）

1. 特許取得

なし

2. 実用新案登録

なし

3. その他

特になし

厚生労働科学研究補助金（循環器疾患等生活習慣病対策総合研究事業）
分担研究報告書

脊髄障害防止の観点からみた胸部下行・胸腹部大動脈瘤外科治療ないしはステントグラフト治療体系の確立
選択的脊髄動脈灌流及びMEP monitorの意義について

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研究要旨

対麻痺は脊髄虚血に起因する合併症として重要であるが、CT等の飛躍的な発達に伴い胸腹部大動脈瘤手術における術後対麻痺予防策も変遷してきている。胸腹部大動脈瘤手術における脊髄障害の最大の要因は、術中・術後脊髄虚血であるとの観点から我々は1）大動脈遮断遠位側灌流（F-F bypass）、2）多分節大動脈遮断、3）可及的多数の分節動脈再建、4）MEPモニター、さらに2002年以降は5）大動脈遮断による25%以下のMEP電位低下時に選択的脊髄動脈灌流を行ってきた。今回、我々の行っている脊髄虚血の指標であるMEPモニターについて、その信頼性を検討した。

A. 研究目的

我々は胸腹部大動脈瘤手術における要点は、脊髄・腹部臓器を含む所属臓器の保護であると考え、1）大動脈遮断遠位側灌流（F-F bypass）、2）多分節大動脈遮断、3）可及的多数の分節動脈再建、4）MEPモニター、さらに2002年以降は5）大動脈遮断による25%以下のMEP電位低下時に選択的脊髄動脈灌流を行ってきた。今回、我々の行っている脊髄虚血の指標であるMEPモニターについて、その信頼性を検討した。

B. 研究方法

2000年以降MEPモニターを使用した32例の胸腹部大動脈瘤手術症例を対象とした。大動脈遮断前のMEP電位を基礎値100%とし、25%以下への電位低下を有意とし、MEP電位有意低下時には30-50mmHgで流量20-50ml/min/1分節動脈の選択的灌流を行った。選択的灌流にてMEP電位が回復した場合Critical arteryと判断し再建する方針とした。

術中MEP電位変化と術後対麻痺発症との関連より4つに分類した。MEP電位変化がなく、対麻痺合併なしを***陰性***、MEP電位が25%以下に低下し、対麻痺合併ありを***陽性***、MEP電位が低下したにもかかわらず、対麻痺合併なしを***偽陽性***、MEP電位変化がないにもかかわらず、対麻痺を合併した場合を***偽陰性***とした。

同時期に施行した胸部大動脈血管内ステント内挿術（TEVAR）症例中MEPモニターを行った6例について検討した。TEVAR症例においてはMEP電位の低下時は昇圧剤投与により平均血圧を維持することで対応した。

（倫理面への配慮）

C. 研究結果

対象 32 例の年齢は平均 61.6 歳。真性 23 例、解離 9 例で 7 例(21.9%)が緊急手術症例であった。平均分節大動脈遮断回数は 2.7 回、分節動脈再建は 24 例 (75.0%) で行われ、再建数は平均 1.5 対であった。大動脈遮断後、MEP 電位が 25%以下に低下したのは 16 例 (50.0%) で、うち 1 例は平均遠位側灌流圧を 50mmHg から 70mmHg に上昇させることで baseline まで回復、10 例 (62.5%) では選択的分節動脈灌流にて baseline まで回復し、当該分節動脈を再建した。手術終了時 MEP 電位が低下・消失したままは 5 例であったが、選択的分節動脈灌流が可能であった 3 例においては、対麻痺は認なかった。

胸部大動脈血管内ステント内挿術 (TEVAR)症例 6 例の年齢は平均 75.5 歳であった。真性瘤 4 例、仮性瘤 1 例、慢性解離 1 例であった。1 例にステントグラフト展開後、血圧の低下に伴い MEP 電位の消失を認めたが、昇圧剤投与により、平均血圧を 80mmHg 以上に維持することで MEP 波形が出現し、電位も速やかに回復した。本症例は術後も血圧を比較的高めに管理し、術後対麻痺を認めなかった。

D. 考察

現行の我々の手術方法では MEP 電位が 25%以上を保っていれば脊髄虚血は回避されており対麻痺合併は認められなかった。MEP 電位が 25%以下に低下或いは消失すれば脊髄虚血は否定し得ず、その 40%において対麻痺をきたした。術中 MEP 電位の変化は多因子性で今後も検討すべきであるが、我々の行っている選択的分節動脈灌流は有用であると思われた。

E. 結論

未だ対麻痺合併の完全なる予防策はなく、MEP モニターは現時点では最も信用しうる指標であると思われた。

F. 健康危険情報

特になし

G. 研究発表

1. 論文発表

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H. 知的財産権の出願・登録状況 (予定を含む)

1. 特許取得

特に無し

2. 実用新案登録

特に無し

3. その他

特に無し

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脊髄障害防止の観点からみた胸部下行・胸腹部大動脈瘤外科治療ないしはステントグラフト治療体系の確立

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研究要旨：胸部下行・胸腹部大動脈手術において、術前のMRIやCTによるAdamkiewicz動脈の同定実施が胸部下行・胸腹部大動脈手術およびステントグラフト治療中の脊髄障害発生に与える影響（発生防止のための有効性）について多施設で検討する。同時に、脊髄障害発生に与える要因を検討することにより、脊髄障害発生率の軽減、治療成績の向上を目的とする。さらに、Adamkiewicz 動脈の同定に関して、部位、同定可能割合について多施設共同コホート研究(前向きおよび後ろ向き)にて調査し、同定技術の向上につなげる。

A. 研究目的

近年、大動脈瘤外科治療全体の成績向上が得られているが、胸腹部大動脈瘤の外科治療は手術侵襲も大きく成績は決して良好とは言えない。特に、術中の脊髄障害（対麻痺）は重要な問題で、広範囲胸腹部大動脈手術においては 10～20％の頻度で発生し、やや低いとされるステントグラフト治療においても 5～10％に発生する。したがって従来より、① 軽度低体温下の部分体外循環や左心バイパスによる下半身灌流法あるいは超低体温下の循環停止法、② MRI・CTを用いたAdamkiewicz動脈の同定、③ 運動誘発電位（motor evoked potential、MEP）などによる術中脊髄虚血のモニタリング、④ 肋間・腰動脈の温存・再建、⑤ 脳脊髄液ドレナージ、⑥ 薬物療法、など様々な脊髄障害防止対策が試みられてきた。しかしながら、明らかなエビデンスに乏しく、一施設での症例数にも限界があり、各施設で独自の防止対策を行っているのが現状で、未だ標準化された脊髄障害防止対策の確立に至っていない。そのような中で、脊髄の栄養血管として主に第8胸椎から第1腰椎の範囲の大動脈から分岐し肋間（腰）動脈を経て脊髄前面に至るAdamkiewicz 動脈が存在し、脊髄障害の防止のためにはその血行再建の必要性が指摘されている。しかしながら、術中限られた時間内で、手がかりもなくAdamkiewicz 動脈へとつながる責任肋間（腰）動脈を正確に同定し、かつその血行再建を成功させることは容易なことではない。したがって、術前にAdamkiewicz 動脈をMRI・CTにより脊髄への血流パターンを把握することは、確実な Adamkiewicz 動脈血行再建を含め手術全体の戦略を立てる上で極めて有用と考える。本研究の目的は、胸部下行・胸腹部大動脈手術において、術前の MRI・CT による Adamkiewicz 動脈の同定実施が脊髄障害発生に与える影響（発生防止のための有効性）について検討する。さらに、胸部下行・胸腹部大動脈手術およびステントグラフト治療における脊髄障害発生に与える要因を検討することにより、脊髄障害発生率の軽減、治療成績の向上を目的とする。

B. 研究方法

① 胸部下行・胸腹部大動脈手術もしくはステントグラフト治療を施行された(る)患者において、MRI・CTによる Adamkiewicz 動脈の同定実施が脊髄障害発生に与える影響を多施設共同コホート研究（前向きおよび後ろ向き)にて検討する。② 胸部下行・胸腹部大動脈手術もしくはステントグラフト治療を施行される患者において、脊髄障害および院内死亡の発生に影響を与える要因について多施設共同コホート研究(前向き)にて検討する。③ Adamkiewicz 動脈の同定に関して、部位、同定可能割合について多施設共同コホート研究(前向きおよび後ろ向き)にて調査する。

1)研究対象:① 胸部下行、胸腹部大動脈手術もしくはステントグラフト治療を施行された患者、② 2000年1月から2010年12月までに手術を施行された患者、③ 倫理委員会承認後に登録を行う患者に対しては、同意能力があり、自ら同意文書に署名できる患者

2)研究デザイン:多施設共同コホート研究(13施設)

3)目標症例数:① 下行大動脈瘤 1,100～1,320例、② 胸腹部大動脈瘤 550～770例

4)評価項目:

主要評価項目:退院までの脊髄障害発生割合

副次評価項目:

(1) Adamkiewicz 動脈の同定方法

(2) Adamkiewicz 動脈の部位

(3) Adamkiewicz 動脈の同定可能割合

(4) 手術による院内死亡割合

(5) 合併症の発生割合

(6) 下記項目の評価

① 手術:術式(置換範囲)、補助手段、循環停止時間、心筋虚血時間、体外循環時間、手術時間、麻酔時間

② 出血:術後出血、輸血量(MAP、FFP)、血小板輸血

③ 回復:挿管時間、ICU 滞在日数、術後入院期間

④ 遠隔期調査における死亡割合、など

(倫理面への配慮)

本研究はヒトを対象とした臨床研究であり、ヘルシンキ宣言に基づく倫理原則、臨床研究に関する倫理指針、疫学研究に関する倫理指針、ならびに本邦における法的規制要件を遵守し実施する。患者を登録する前に、研究実施計画書について、各施設に倫理委員会または審査委員会から文章による承認を得る。患者への同意・説明文書には、試験データは研究者により厳重に保護される旨説明される。前向き研究においては、研究担当医師は、登録までに本研究についての内容を患者本人に説明し、参加について文書による同意を患者本人より得るものとする。同時に、当該研究の目的を含む研究の実施についての情報を公開し、研究対象者となる者が研究対象者となることを拒否できるように配慮する。また、実施計画書は、患者本人の希望により、いつでも閲覧できることとする。本研究で得られた個人情報は画像情報も含め厳重に保護し、個人を特定できる情報は開示しないなど取り扱いには十分留意する。本研究は研究対象者の自発的同意と協力により行い、その段階でも同意を撤回拒否でき、拒否による不利益はないものとする。

C. 研究結果

2010年1月末の時点で230例(Adamkiewicz 動脈の同定実施 78.7%)の症例登録があった。中間解析を行った結果, Adamkiewicz 動脈の同定のうちわけは、確実 52.1%、可能性 13.0%、不可能 13.9%、不明 0.4%であった。脊髄障害の発生は、完全対麻痺 1.3%、不完全 5.2%、なし 86.2%、判定不能 6.5%、その他 0.8%であった。胸腹部大動脈瘤(97例)に対象を絞って解析すると、脊髄障害 6.1%であった。

D. 考察

電子媒体を用いた登録システムの構築に時間を要したが、症例登録は順調に進んでいる。中間解析の結果、Adamkiewicz 動脈の同定に関しては、確実

65.4%、可能性 17.0%と 8 割以上の症例において Adamkiewicz 動脈の同定が可能であった。胸部下行・胸腹部。胸腹部大動脈治療における脊髄障害防対策の一つとして、Adamkiewicz 動脈の同定とそれを利用した治療戦略が挙げられるが、8 割の症例において同定できており、その有用性が改めて示唆されたと考える。同時に、中間解析の一部、特に胸腹部大動脈治療において Adamkiewicz 動脈同定実施の脊髄障害防止に対する有効性が示唆された。ただ、有意差なく傾向のみに止まった。背景として、ステントグラフト治療例や Crawford 分類 IV 型など、脊髄障害が比較的発生しにくいとされている症例において Adamkiewicz 動脈の同定が実施されていないなどが影響しているものと考える。最終的な詳細な解析結果が待たれるところである。

F. 結論

中間解析の結果、胸腹部大動脈治療において Adamkiewicz 動脈同定実施の脊髄障害防止に対する有効性（傾向のみ）が示唆されたが、最終の詳細な解析結果が待たれる。

E. 健康危険情報

なし。

G. 研究発表

1）論文発表

1. Minatoya K, Ogino H, Matsuda H, Sasaki H, Yagihara T, Kitamura S. Replacement of the descending aorta: recent outcomes of open surgery performed with partial cardiopulmonary bypass. J Thorac Cardiovasc Surg. 136(2):431-5, 2008.

H. 知的財産権の出願・登録状況（予定を含む）

1. 特許取得

なし。

2. 実用新案登録

なし。

3. その他

なし。

III. 研究成果の刊行物・別刷

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Hybrid treatment for aortic arch and proximal descending thoracic aneurysm: experience with stent grafting for second-stage elephant trunk repair[☆]

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Abstract

Background: Aortic aneurysm affecting the arch and proximal descending thoracic aorta may require a two-stage repair, which includes proximal elephant trunk graft placement and completion of descending thoracic aortic repair. The combination of open surgery and endovascular grafting may improve the morbidity and mortality of the patient population at risk. **Methods:** Between February 2001 and March 2007, 258 patients underwent thoracic aortic endovascular grafting at our institution, wherein 31 patients underwent a hybrid approach involving proximal arch repair and elephant trunk graft replacement, and endovascular completion procedures. All patients, who underwent combined endovascular and open procedures in the management of the aortic arch and proximal descending thoracic aortic aneurysms, were reviewed and analysed retrospectively. **Results:** The interval between the first and second stage ranged from 0 to 14 months with a mean interval of 3.1 months. Follow-up ranged from 0 to 70 months with a mean of 31 months. Technical success was achieved in all patients. The 1, 12, 36 and 60-month mortality rates were 6.4%, 16.5%, 26.7% and 26.7%, respectively. Caudal migration of the endograft occurred in three patients, who underwent conversion to open surgery. Two cases of paraparesis but no paraplegias or strokes were recorded. **Conclusions:** Staged procedures using endovascular grafting in the treatment of the arch and proximal descending thoracic aneurysm may have the potential to reduce morbidity and mortality rates. Although long-term results are still pending, this early experience demonstrates the safety and early-term effectiveness of this hybrid approach, which consists both of endovascular and open surgical procedures.

Keywords: Aneurysm; Elephant trunk; Endovascular; Stent-graft

1. Introduction

Treatment of extensive aortic aneurysms involving the ascending aorta, aortic arch and descending aorta is still considered to be a challenge for many cardiovascular surgeons. Single-stage operations entail large incisions and substantial mortality risk. The introduction of the elephant trunk technique by Borst et al. [1] in 1983 has greatly facilitated multiple-stage surgery for an extensive thoracic aortic aneurysm. Therefore, many surgeons have preferred a two-stage approach in the treatment of combined lesions of the aortic arch and descending aorta. In the two-stage approach, initially, the aorta in the ascending part and transverse arch is repaired through a median sternotomy. For second-stage operation, the graft replacement of the descending aorta has been performed through left thoracotomy.

Since the introduction of endovascular stent-graft technology for thoracic aortic aneurysms by Dake et al. [2] in 1998, the procedure has been considered as an alternative treatment modality with associated reduced mortality and morbidity for thoracic aortic aneurysms. The benefits of stent-graft repair of thoracic aortic aneurysms may be combined with conventional open surgery in order to include extensive aortic aneurysms, which would otherwise be unsuitable for repair by endovascular therapy alone. To evade the invasive procedure of left thoracotomy for descending thoracic aortic aneurysms in second-stage operation, we advocate the less-invasive endovascular stent grafting in fixing the elephant trunk. Therefore, the elephant trunk could be the most suitable condition as proximal neck of the stent graft; and endovascular repairs have been selectively employed in place of the next operation [3–10].

To date, the application of endovascular stent-graft repair in the treatment of patients with extensive aortic aneurysms

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remains an area of general debate. In this study, we conducted a review on our experience on the management of extensive aortic aneurysms using elephant trunk repair with endovascular stent-grafting exclusion at distal site.

2. Materials and methods

2.1. Patients

Between February 2001 and June 2008, 258 patients underwent thoracic aortic endovascular grafting at our institution. Thirty-one patients underwent a hybrid approach involving proximal arch repair with elephant trunk graft replacement and endovascular completion procedures. A retrospective review on the combined endovascular and open procedures in the management of aneurysms of the arch and proximal descending thoracic aorta was performed. Data from the hospital records of the patients were obtained from our departmental registry. The patients included 24 males and seven females, with a mean age of 70 years (range: 39–83 years). Aortic pathology included 27 atherosclerotic aneurysms and four aortic dissections. The maximal aortic diameters ranged from 50 to 80 mm (mean: 63 mm) with computed tomography (CT) scanning. The patients' characteristics are summarised in Table 1.

2.2. Open proximal repair

The patients underwent conventional surgery for aneurysms of the ascending aorta and transverse arch through a median sternotomy using cardiopulmonary bypass, hypothermic circulatory arrest and antegrade selective cerebral perfusion as first-stage elephant trunk repair of the aneurysm. Cardiopulmonary bypass was performed as follows: perfusion of the right axillary artery with a side graft sewn onto the axillary arteries and vena cava drainage in 29 (93.5%) patients and cannulation of the ascending aorta and vena cava drainage in two (6.5%) patients. In all patients, antegrade selective cerebral perfusion using a balloon

Table 1
Demographics, comorbidities of hybrid operation.

Demographics	
No. of patients	31
Age (year)	70 ± 9
Male gender (%)	24 (77)
Aneurysm diameter (mm)	63 ± 8
Comorbidities, *n* (%)	
Hypertension	24 (77)
Hyperlipidemia	10 (32)
Diabetes	4 (13)
Smoking	5 (16)
Coronary artery disease	4 (13)
Chronic obstructive pulmonary disease	4 (13)
Chronic renal insufficiency	3 (9.7)
Marfan syndrome	1 (3.2)
Renal failure (dialysis)	0 (0)
Pathology of aneurysmal dilatation, *n* (%)	
Aortic dissection	4 (13)
Non-dissection	27 (87)
Mean interval between two stages (month)	3.1

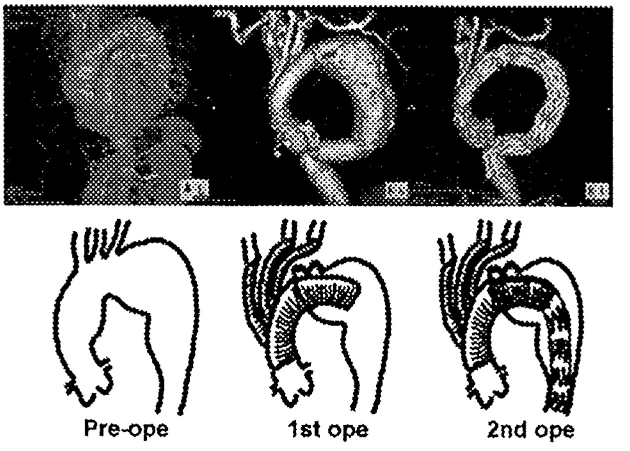

Fig. 1. Aortic aneurysm affecting the arch and proximal descending thoracic aorta requires a two-stage repair, which includes proximal elephant trunk graft placement and completion of descending thoracic aortic repair.

catheter for 33–256 min (mean: 91 ± 41 min) was done. Pump times were 115–356 min (mean: 177 ± 59 min). The average temperature indicative of circulatory arrest on rectal temperature monitoring was 24 ± 2.5 (range: 15.7–28.0) (Fig. 1) (Table 2).

All the elephant trunks were made of Dacron graft (Hemashield® (BostonScientific Corp., Wayne, NJ, USA), or Gelweave® (TERUMO CardioVascular Systems Corp., Ann Arbor, MI, USA)) with a diameter of 22–30 mm and length of 60–150 mm. In one patient, the elephant trunk was anastomosed at the base of the innominate artery. In 14 patients, the anastomosis of the elephant trunk was placed in the aortic arch between the left carotid and left subclavian arteries. The spinal cord function remained intact throughout the procedure.

2.3. Stent-graft placement

The stent grafts were hand-made using Gianturco Z-stents (Cook Inc., Bloomington, IN, USA), which were pre-constructed to fit the aortic tortuosity, covered with a UBE prosthetic vascular graft (Ube Corp., Ube, Japan). We use various types (9-, 12-, 16- and 20-cm lengths using 20-, 30- and 40-mm wide stents) of 2.5-cm-long Z-stents as endoskeletons, which were previously gas-sterilised, then stored in our hospital for immediate use. Z-stents were attached to each other with solder, leaving spaces of 8 mm between the stents.

Axial CT images were used to determine the diameter of the landing zone and the length of the endoskeleton. The procedure has been described in detail in a previous report [11]. Briefly, the patient was placed on a radiolucent operating table under general anaesthesia in the operating room. The hand-made stent graft was manually loaded into the proximal end of an 18–22 F sheath (Cook Inc.), depending on the dimensions of the stent graft. The delivery system was advanced to the target region over the guide wire. The sheath was withdrawn after DSA confirmed the exact localisation in relation to the head vessels, elephant trunk and diseased aortic segment. For patients with dissection, the position of the guide wire into the true

Table 2
Details of the first-stage and second-stage operation.

First-stage operation	
Number of patients	31
Concomitant operative procedure, *n* (%)	
CABG	3 (9.7)
Extracorporeal circulation	
Axillary arterial cannulation, *n* (%)	29 (94)
Cardiopulmonary bypass time (min)	177 ± 59
Selective cerebral perfusion time (min)	91 ± 41
Myocardial ischemic time (min)	90 ± 43
Systemic arrest time (min)	38 ± 21
Minimum rectal temperature (°C)	24 ± 2.5
Elephant trunk anastomosis site, *n* (%)	
Proximal inominate artery	1 (3.2)
Between inominate and left carotid arteries	12 (39)
Between left carotid and subclavian arteries	14 (45)
Distal of left subclavian artery	4 (13)
Elephant trunk size (cm)	26 ± 2.2
Elephant trunk length (cm)	8.8 ± 2.6
Complication *n* (%)	
Cerebral infarction (temporary)	1 (3.2)
Second-stage operation	
Number of patients	31
Technically successful, *n* (%)	31 (100)
Number of Z-stent inserted in elephant trunk graft	1.5 ± 0.4
Endovascular device used, *n* (%)	
Homemade	31 (100)
TAG	0 (0)
Vertebral level of distal end of stent-graft, *n* (%)	
Th5	1 (3.2)
Th6	5 (16)
Th7	5 (16)
Th8	14 (45)
Th9	2 (6.5)
Th10	0 (0)
Th11	2 (6.5)
Th12	1 (3.2)
L1	1 (3.2)
Technically successful, *n* (%)	31 (100)
Endoleak, *n* (%)	
Type 1	1 (3.2)
Type 2	2 (6.5)
Type 3	0 (0)
Complication, *n* (%)	
Cerebral infarction (temporary)	0 (0)
Paraparesis	2 (6.5)
Paraplegia	0 (0)

lumen was verified with intravascular ultrasonography. When a post-procedural DSA demonstrated an endoleak, balloon dilatation was performed. The elephant trunks were constructed with Dacron grafts that ranged in diameter from 20 to 26 mm. Stent-graft diameters were selected with an oversizing of 15–20% relative to the diameters of the Dacron grafts, which were the proximal stent grafts. Stent grafts were inserted in an elephant trunk longer, as much as possible. Of 31 patients, tapered stent grafts were used in 10, because the diameter of the descending thoracic aorta in those patients was significantly larger than the diameter of elephant trunk prosthesis. The elephant trunk is the proximal landing zone, and the diameter of the stent graft is decided only according to the diameter of the descending thoracic aorta for the distal landing zone. Stent grafts used in the treatment of the above conditions usually have a tapered design.

2.4. Statistical analysis

Statistical analyses were performed using the SPSS 11.0 software (SPSS Inc., Chicago, IL, USA). All values were expressed as mean ± standard deviation. Kaplan–Meier curves were compared using a log-rank test.

3. Results

3.1. Open surgical procedure for first operation

There were no procedure-related deaths after the first-stage operation. One patient suffered from temporary stroke (3.2%). All patients underwent second-stage procedure, and the interval between the first and second stages ranged from 0 to 14 months (mean: 3.1 months). No patients were lost to follow-up.

3.2. Stent-graft placement for second operation

Stent-graft repair was technically successful in all patients. Two of 31 patients had endoleaks identified on follow-up CT scans. These were classified as type 2 endoleaks because the CT scan demonstrated a small area of contrast emanating from the intercostal arteries, with no further contrast visualised in the remainder of the aneurysm sac on both axial and reconstructed images. All patients had an endovascular stent graft inserted into the elephant trunk prosthesis at the proximal site. The vertebral level of the distal end of the stent graft was within the level of Th5 to L1 in all cases (Table 2).

3.3. Morbidity and mortality

Two hospital deaths (6.4%) occurred after the second-stage operation (Table 3). The first death recorded was a women who died on postoperative day 3 due to intestinal ischaemia from superior mesenteric artery embolism. The second death was a man who died on postoperative day 37 because of sepsis. No postoperative paraplegia was observed, but paraparesis was noted in two patients, one of whom died during hospitalisation, while the other patient was discharged ambulatory.

The 2- and 5-year mortality rates (by Kaplan–Meier analysis) were 16.5% and 26.7%, respectively (Fig. 1). No re-operation was recorded on 78.3% of cases after 5 years (Fig. 2).

Caudal migration of the endograft occurred in three patients, who underwent conversion to open surgery. Left thoracotomy after the second-stage procedure was

Table 3
Operative mortality.

	Mortality	
	No. of 30-day (%)	No. of hospital (%)
First-stage operation	0	0
Second-stage operation	1 (3.2)	2 (6.4)

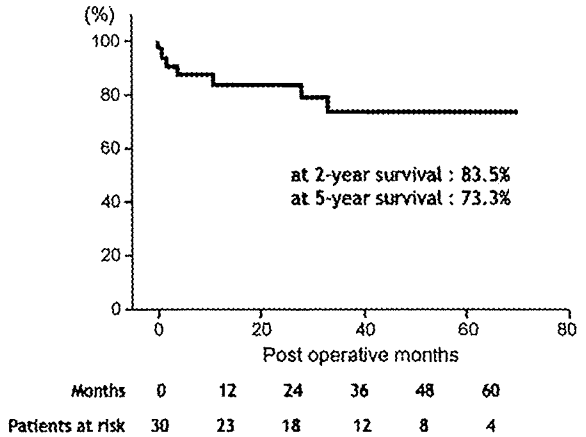

Fig. 2. Survival after two-stage repair of extensive aortic aneurysms. Kaplan–Meier estimate of survival for patients who underwent two-stage repair. Survival probability at 2- and 5-year were 83.5 ± 6.8% and 73.3 ± 9.0%.

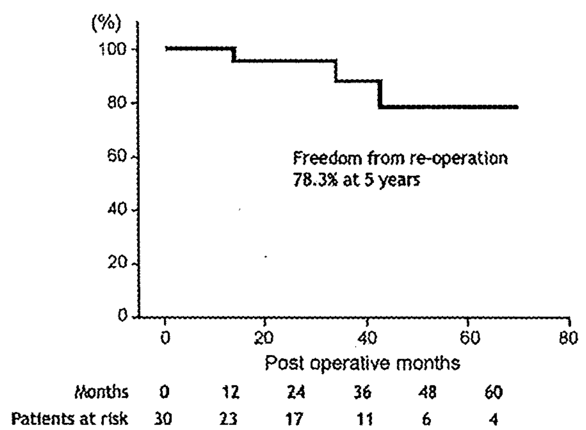

Fig. 3. Freedom from migration of stent-grafts related re-operation. Kaplan–Meier estimate of freedom from re-operation for patients who underwent two-stage repair. Freedom from re-operation at 5 years was 78.3 ± 11.7%.

performed for graft replacement because of expansion of the descending thoracic aneurysm from the endoleak at the proximal neck of the stent graft (Fig. 3).

4. Discussion

In order to accomplish extensive replacement of the aorta with one-stage approach, several operative methods have been devised. Despite acceptable results early on, the said approach appears not to be widespread probably because of its complexity or invasiveness. After earlier publications from Borst and co-workers and Crawford's landmark paper published in 1990 [12], this method became increasingly popular for the treatment of patients with complex aortic disease [13–15]. The elephant trunk procedure has been developed to facilitate multiple-stage surgery for extensive thoracic aortic aneurysm. The idea of using the elephant trunk prosthesis as a stent graft to be introduced in the descending aorta was initiated and popularised by the Buffolo group [16], who employed this approach in a large series of patients with acute type B dissection.

In this study, we noted that the mortality associated with the endovascular procedure was exceptionally low and, coupled with a low rate of neurological complications or other serious adverse events, the endovascular completion of arch and elephant trunk repairs can be performed safely. Along with the advent of transfemoral stent grafts for the treatment of descending aortic aneurysms, it has been possible to securely anchor a stent graft in an elephant trunk prosthesis previously placed during arch surgery [2]. The list of published series of endovascular completion after previous elephant trunk procedure is summarised in Table 4 [3–10]. Although this cohort is relatively small, the procedural results seem promising with a low risk for paraplegia. If the anatomical condition is suitable for an endovascular procedure, in other words, if the distal landing zone could be secured, this endovascular completion may be an alternative to the conventional second-stage operation. Although no permanent paraplegia occurred in the present study, the use of this technique must be contrasted with the open surgical approach, in which the potential to re-implant intercostals exists.

The frozen elephant trunk technique, an alternate method to achieve one-stage repair of extensive aortic disease through median sternotomy, evolved into a hybrid procedure combining the concepts of elephant trunk principle and endovascular stenting of descending aortic aneurysms. It was introduced in the late 1990s as the 'open stent-grafting' technique and was renamed 'frozen elephant trunk' [21]. With this approach, repair of the aortic arch is performed conventionally through a median sternotomy with hypothermic circulatory arrest and antegrade cerebral perfusion. The frozen elephant trunk technique was not employed in our study because the summarised rate of paraplegia after implantation of the frozen elephant trunk was 4.7%, in which Flores et al. and Miyairi et al. reported a relatively high rate (16% and 21%, respectively) of post-operative paraplegia, as presented in Table 5 [17–25].

The length of the elephant trunk graft is intended to provide a region of adequate overlap for stent-graft insertion. However, excessive length of the elephant trunk graft or marked arch tortuosity can make the endovascular portion of the repair more complicated and possibly less durable. Our total elephant trunk graft length is 6–15 cm (mean: 8.8 cm). According to Borst's original suggestion, the

Table 4
Surgical series of previous conventional elephant trunk technique + endovascular completion.

Author	Year	Mortality at endovascular completion	Paraplegia at endovascular completion	Reference
Brat et al.	2006	0/3 (0%)	0/3 (0%)	[3]
Azizzadeh et al.	2006	0/1 (0%)	0/1 (0%)	[4]
Greenberg et al.	2005	1/22 (4.5%)	0/22 (0%)	[5]
Carroccio et al.	2005	1/12 (8.3%)	0/12 (0%)	[6]
Matsuda et al.	2005	0/4 (0%)	0/4 (0%)	[7]
Wolthuis et al.	2005	0/1 (0%)	0/1 (0%)	[8]
Wong et al.	2001	0/1 (0%)	0/1 (0%)	[9]
Fann et al.	1995	0/1 (0%)	0/1 (0%)	[10]
Total		2/45 (4.4%)	0/45 (0%)	

Table 5
Frozen elephant trunk (open stent-grafting) procedure.

Author	Year	Mortality	Paraplegia	Reference
Baraki et al.	2007	5/39 (12.8%)	0/39 (0%)	[17]
Liu et al.	2006	2/60 (3.3%)	1/60 (1.6%)	[18]
Flores et al.	2006	3/25 (12%)	4/25 (16%)	[19]
Uchida et al.	2006	2/35 (5.7%)	0/35 (0%)	[20]
Karck et al.	2003	0/4 (0%)	0/4 (0%)	[21]
Mizuno et al.	2003	1/8 (12.5%)	1/8 (12.5%)	[22]
Fleck et al.	2002	1/8 (12.5%)	0/8 (0%)	[23]
Miyairi et al.	2002	2/19 (10.5%)	4/19 (21.1%)	[24]
Orihashi et al.	2001	1/15 (6.7%)	1/15 (6.7%)	[25]
Total		17/213 (8.0%)	11/213 (5.2%)	

length of the elephant trunk depends on the extent of the downstream aortic enlargement and should be at least 7–8 cm. A potential problem of this variant is the likelihood of complications due to kinking and graft occlusion because of the long elephant trunk. This suspicion is supported by Crawford's finding of increased risks of peripheral embolisation caused by the flapping action of the elephant trunk and paraplegia, as a result of clot formation around the graft if the trunk is long [12].

In our study, three cases were converted to open surgery after second-stage operation due to enlargement of the aneurysm because of endoleak from the overlap portion. We were unable to provide a region of adequate overlap for stent-graft insertion during the second-stage operation because of the tortuosity or kinking of the elephant trunk graft. Tortuosity of the proximal repair site was noted as a result of the inherent structure of the aneurysmal arch or induced by the elephant trunk graft.

The length of the elephant trunk limb can also be variable. However, we have recently selected a relatively short limb (8–10 cm) for elephant trunk prosthesis to ease cannulation from below and to avoid the conversion to open surgery for second-stage operation. This length also provides more than adequate overlap for the proximal landing zone and can prevent tortuosity or kinking after the insertion of elephant trunk graft. This effect complicates the analysis on the stability of the endograft position (migration) and underscores the importance of radiographic landmarks on the elephant trunk at the time of surgical implantation.

If a stent graft conducted during the second-stage operation can be smoothly inserted into the elephant trunk prosthesis inserted during the first operation, endoleak resulting from tortuosity or migration can be prevented. Proper insertion of the stent graft must be ensured and an elephant truck excess in length must not be used. Additionally, a stent-graft is required to reach the distal anastomosis site of the elephant trunk, which is not fixed in the aneurysm. Consequently, we believe that endovascular completion of an elephant trunk is feasible.

5. Conclusion

Staged procedures using endovascular grafting in the treatment of the arch and proximal descending thoracic aneurysm may have the potential to reduce morbidity and mortality rates. Although long-term results are still pending, this early experience demonstrates the safety and early-term effectiveness of this hybrid approach, which consists both of endovascular and open surgical procedures.

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Appendix A. Conference discussion

Dr H. Jakob (***Essen, Germany***): Congratulations on outstanding results with this less-invasive two-stage approach combining classic aortic arch surgery including the elephant trunk technique with delayed TEVAR. Zero mortality for Stage I and a 6.4% mortality for Stage II with a 5-year survival rate of 73% for a mean 70-year-old patient population and a 78% freedom from re-operation for the same time interval, unsurpassed results. Many questions arise, but I think for time's sake, I will restrict myself to three questions. So from Dr Safi's report, we have learned that between the two stages, there is a substantial mortality of at least 10%. So what were your decision criteria to delay the second stage up to 14 months? You have a mean delay of 3.1 months between both stages.

Dr Kawaharada: Fortunately, I did not experience that procedure-related death of the patient after the first-stage operation. We were very careful to increase of the blood pressure. And we had a mean delay of 3.1 months between both operations because we had waiting to recover the patient's condition. It is important for us to recover patient's physical strength. We decided the second operation schedule by the enough recovery of the physical strength of the patient.

Dr Jakob: Okay. My second question regarding your stent-graft design, you mentioned that you're oversizing 15–20% in relation to the elephant trunk diameter. Example given, so you have a 26-mm elephant trunk diameter plus 20% ends up with a 32-mm stent-graft diameter. What diameter of the distal landing zone do you accept?

Dr Kawaharada: We use the homemade stent-graft in these operations. So if we made the stent-graft for elephant trunk prosthesis size, we could change the size of the stent-graft for distal landing zone by tapering the stent-graft.

Dr Jakob: Okay. My third question, you observed caudal migration of the endograft in three patients so roughly 10%. How did those patients make the re-operation? You did not mention that. Did they survive? Mean age was 70 years, and the time interval was 3.6 years I think I've seen from the slide. So all three patients survived?

Dr Kawaharada: We did not perform endovascular surgery for these migration cases. So three patients who had caudal migration underwent the graft replacement through left thoracotomy.

Dr C. Mestres (***Barcelona, Spain***): Okay. I think the question was, were they alive or dead? Do you understand? The question is if the three patients were alive or dead?

Dr Kawaharada: These three patients were all alive.

Dr Mestres: Okay. Thank you. Now we understand.

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Institutional report - Vascular thoracic

Spinal cord protection with selective spinal perfusion during descending thoracic and thoracoabdominal aortic surgery☆

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Institutional Report

Abstract

Open repair of aortic aneurysm causes spinal cord perfusion pressure to decrease due to the steal phenomenon from the bleeding of intercostal arteries and cross-clamping of the aorta. We attempted to perfuse the intercostal arteries for preoperative detection of the artery of Adamkiewicz using newly developed catheters. Fifteen patients underwent selective spinal perfusion with our original catheter as spinal protection during the procedure of distal descending thoracic aneurysm (DTA) or thoracoabdominal aortic aneurysm (TAAA) repair. Seven patients had distal DTA and eight had TAAA. Monitoring of motor evoked potential (MEP) was performed in all patients throughout the operation. The perfusion flow was 30–40 ml/min for each intercostal artery and was adjusted to keep the proximal circuit pressure at 150–200 mmHg. The average number of perfused intercostal arteries was 2.3 per patient and the number of intercostal arteries reimplanted per patient was 2.5. Intercostal arteries were reimplanted using an interpositional graft. MEPs were still observable after graft replacement in all patients and there were no cases of paraparesis/paraplegia. All patients were discharged ambulatory. Selective spinal perfusion maintains the quantity of total blood flow in the spinal cord and is very useful for reducing the incidence of ischemic injury of the spinal cord during operation.

Keywords: Aneurysm; Motor evoked potential; Spinal cord; Selective spinal perfusion

1. Introduction

Postoperative paraplegia or paraparesis is a serious complication of reconstructive surgery on the thoracoabdominal or descending thoracic aorta, wherein the major cause is thought to be spinal cord ischemia during and after the procedure. Due to advances in anesthetic and surgical techniques, the incidence of intractable neurological complications has declined, but the rate of paraplegia or paraparesis is still within the range of 4–16% [1, 2]. In the thoracolumbar region, it is known that the great anterior medullary artery [artery of Adamkiewicz or arteria radicularis magna (ARM)] is the dominant feeder of the spinal cord. One cause of paraplegia after aortic operations is the failure to re-establish the spinal cord blood supply.

Consequently, it has been suggested that reattachment of the intercostal and lumbar arteries during replacement of a descending thoracic or thoracoabdominal aorta could minimize such complications [3]. The importance of reattachment of the intercostal artery related to the ARM has been stressed in many reports. To avoid neurological complication, it is useful to know the level of the intercostal artery from which the ARM originates before reconstructive aortic surgery [4]. Even when the important segmental artery is successfully preserved, transient ischemia may occur during reimplantation and cause spinal cord injury. Thus, when reattachment of the segmental arteries is necessary, perfusion of these vessels during anastomosis will reduce spinal cord ischemia.

We investigated the outcome of thoracoabdominal or descending thoracic aortic aneurysm repair after selective perfusion to the intercostal arteries during operation and preoperative detection of the ARM by magnetic resonance angiography (MRA) or multi-detector-row computed tomography (MDCT) to prevent neurological deficit.

2. Materials and methods

2.1. Patients

Between February 2007 and March 2009, 15 patients underwent selective spinal perfusion with original catheters as spinal protection during the surgery of distal descending thoracic aneurysm (DTA) or thoracoabdominal aortic aneurysm (TAAA) repair. A retrospective review on selective spinal perfusion procedure in the management of DTA or TAAA was performed. Data from the hospital records of the patients were obtained from our departmental registry.

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2.2. Detection of the artery of Adamkiewicz

Eleven patients underwent MRA for detection of the ARM in this study. The MRAs were performed with a 1.5-T unit SIGNA Infinity Excite (GE Medical Systems, Milwaukee, WI). Four patients were imaged in the supine position with a 64-detector CT system (LightSpeed VCT, GE Health care, Milwaukee, WI, USA) from the apex of the lungs to the pubic symphysis.

2.3. Surgical technique

Arterial pressure was monitored at the right radial artery and at the dorsalis pedis artery opposite the femoral artery that was cannulated for the bypass. After induction of general anesthesia, patients were placed in the left lateral decubitus position with hips swiveled posteriorly. A double-lumen endotracheal tube was used in all patients, allowing collapse of the left lung. Left thoracotomy was performed through the fifth, sixth or seventh intercostal space. Some patients with type I and II TAAA were treated according to a previously reported procedure [5]. The entire aorta was exposed with dissection of the retroperitoneal space and division of the costal cartilage and diaphragm. Cardiopulmonary bypass was established by means of cannulation of the right femoral artery and the right femoral vein basically, after the administration of heparin (2 ml/kg). The femoral venoarterial bypass circuit used for the procedure included a centrifugal pump and a membrane oxygenator with heat exchanger. The circuit was branched for selective perfusion of the segmental arteries and major abdominal vessels. Selective perfusion of intercostal arteries using newly developed catheters was performed with a roller pump independent of systemic circulation. The perfusion flow was 30–40 ml/min for each intercostal artery and was adjusted to keep the proximal circuit pressure at 150–200 mmHg with a roller pump, independent of the cardiopulmonary bypass circuit (Figs. 1 and 2, Video 1). After the intercostal arteries were reconstructed, the visceral and renal arteries were also reimplanted. During reconstruction of the visceral and renal arteries, selective visceral and renal perfusion with 10–12 F balloon catheters connected to the systemic circuit was performed. Each artery was perfused at a flow rate of 200–300 ml/min.

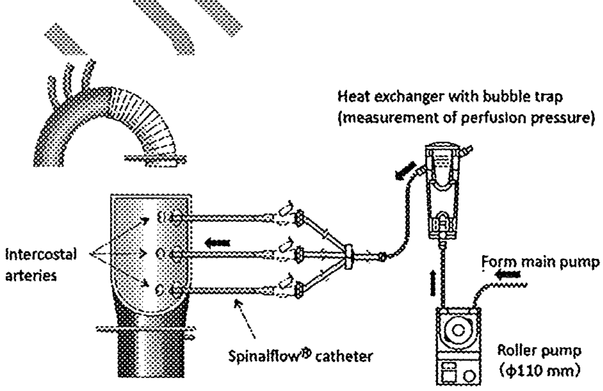

Fig. 1. Selective perfusion of the intercostal arteries using newly developed catheters was performed with a roller pump independent of systemic circulation. The perfusion flow was 20–30 ml/min for each intercostal artery and was adjusted to keep the proximal circuit pressure at 100–200 mmHg with a roller pump, independent of the cardiopulmonary bypass circuit.

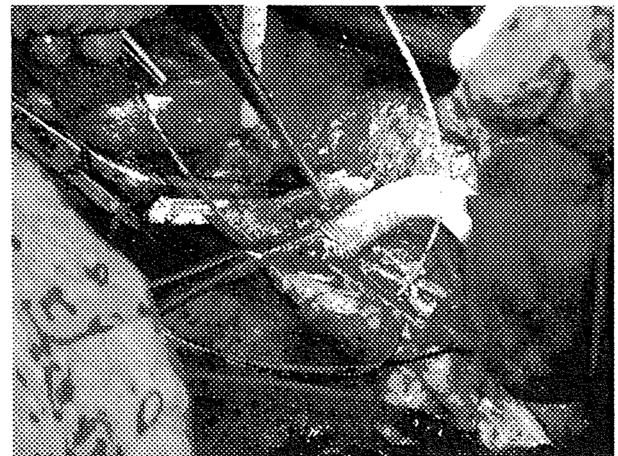

Fig. 2. Intercostal arteries were reattached by separate tube graft under selective perfusion of the intercostal arteries using newly developed catheters for the purpose of maintaining spinal cord perfusion pressure during the cross-clamping of the aorta.

Video 1. Catheters (Spinalflow®, Fuji Systems Co, Ltd, Tokyo, Japan) used in this study are made from polyurethane with a total length of 40 cm, size of 4.4 F, and balloon volume of 0.06 ml. Perfusion flow rates through these catheters measured by blood (Hct: 20%) under 150 and 200 mmHg perfusion pressure were approximately 30 and 40 ml/min, respectively. During reimplantation, we attempted to perfuse the intercostal arteries in all patients.

2.4. Catheters for selective perfusion of intercostal arteries

Catheters (Spinalflow®, Fuji Systems Co, Ltd, Tokyo, Japan) used in this study are made from polyurethane with a total length of 40 cm, size of 4.4 F, and balloon volume of 0.06 ml. Perfusion flow rates through these catheters measured by blood (Hct: 20%) under 150 and 200 mmHg perfusion pressure were approximately 30 and 40 ml/min, respectively [6] (Fig. 3). During reimplantation, we attempted to perfuse the intercostal arteries in all patients.

2.5. Monitoring technique for transcranial motor evoked potentials (Tc-MEPs)

Tc-MEPs were elicited by using a multiple electrical transcranial stimulator (Digitimer D185 cortical stimulator, Digitimer Ltd, Welwyn Garden City, UK). Stimuli were applied to the skull with the anode placed in the C3 position and the cathode in the C4 position (International 10–20 system for the placement of electroencephalogram electrodes). The stimulus consisted of a series of five pulses. Each

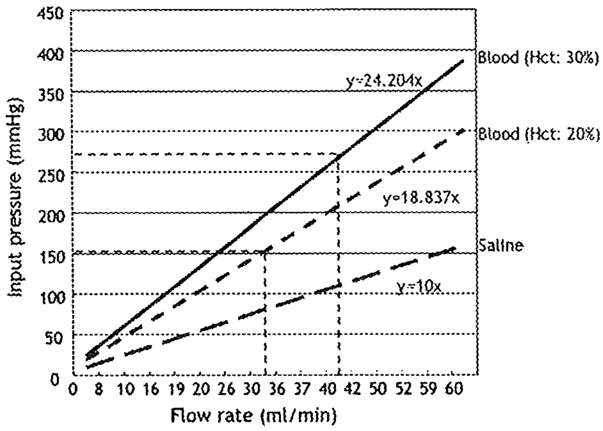

Fig. 3. Pressure loss of Spinalflow® catheter. Perfusion flow rates through these catheters measured by blood (Hct: 20%) under 150 and 200 mmHg perfusion pressure were approximately 30 and 40 ml/min, respectively.

individual stimulation lasted 50 ms, and the interstimulus interval between pulses was 2.0 ms. The output voltage was set at 500 V. Compound muscle action potentials were recorded from the skin over the right flexor hallucis brevis muscle and the right flexor pollicis brevis muscle using adhesive gel Ag/AgCl electrodes. Signals were recorded every 100 ms, passed through a bandpass filter of 10–1000 Hz, and amplified 5000–20,000 times. Data acquisition, processing, analysis, and saving required a personal computer system (Neuropak MEB-2200, Nihon Koden, Tokyo, Japan). An average of three consecutive amplitudes recorded before aortic cross-clamping was defined as the baseline. A reduction of motor evoked potential (MEP) amplitude of the flexor hallucis brevis muscle to <50% of baseline was considered to be a sign of spinal cord ischemia.

2.6. Statistical analysis

Statistical analyses were performed using the SPSS 11.0 software (SPSS Inc, Chicago, IL). All values were expressed as mean ± standard deviation (S.D.).

3. Results

The patients included 12 males and 3 females with a mean age of 65 years (range, 52–79 years). Aortic pathology included five atherosclerotic aneurysms and ten dissecting aneurysms. The maximal aortic diameters ranged from 55 to 79 mm (mean, 65 mm). The patients' characteristics are summarized in Table 1. Seven patients had distal DTA and eight had TAAA (Crawford's classification revealed type 1 in two patients, type 2 in four patients, and type 3 in two patients with prior descending or abdominal aortic repair) (Table 1).

ARMs were detected in 13 (87%) of 15 patients. All 13 patients had vessels that coursed toward the anterior spinal artery and were supplied by the intercostal artery. The laterality of the arteries originated from the intercostal artery on the left side in 10 (77%) of the 13 ARMs. Cerebrospinal fluid (CSF) drainage was used intraoperatively in 10 patients (67%).

Table 1
Demographics and comorbidities of operation

Demographics	
No. of patients	15
Age (years)	62±9
Male gender (%)	12 (80)
Aneurysm diameter (mm)	65±7
Aneurysm type, *n* (%)	
Thoracic	7 (47)
Crawford type 1	2 (13)
Crawford type 2	4 (27)
Crawford type 3	2 (13)
Previous aortic procedure, *n* (%)	8 (53)
Infrarenal AAA, *n* (%)	4 (27)
Thoracic aortic aneurysm, *n* (%)	4 (27)
Comorbidities	
Hypertension, *n* (%)	13 (87)
Hyperlipidemia, *n* (%)	3 (20)
Smoking, *n* (%)	4 (27)
Chronic obstructive pulmonary disease, *n* (%)	2 (13)
Chronic renal insufficiency, *n* (%)	3 (20)
Pathology of aneurysmal dilatation, *n* (%)	
Aortic dissection	10 (67)
Non-dissection	5 (33)
Detection of ARM, *n* (%)	13 (87)

ARM, arteria radicularis magna.

3.1. Selective perfusion and reconstruction of intercostal arteries

The average number of perfused intercostal arteries was 2.3 per patient and the number of intercostal arteries reimplanted per patient was 2.5. Intercostal arteries were reimplanted using an interpositional graft (8 mm or 10 mm). The average perfusion time of ICAs with the catheters or through the implanted interpositional grafts was 64 min (Table 2).

3.2. Changes in MEP after aortic cross-clamp

MEPs were still observable after graft replacement and no case of paraparesis/paraplegia happened. In two patients, MEPs were not observed directly after aortic cross-clamp. The ARM was located in the RT8 and LT10, including the cross-clamp area, in these patients. The changes in MEPs amplitude after cross-clamping were recovered by selective intercostal arteries perfusion (Fig. 4).

Table 2
Intraoperative details

Cardiopulmonary bypass time (min)	214±100
Aortic cross-clamp time (min)	162±80
Distal aortic perfusion, *n* (%)	15 (100)
Distal perfusion time (min)	167±71
Visceral perfusion, *n* (%)	8 (53)
Visceral perfusion time (min)	138±50
Mean selective spinal perfusion time (min)	
With catheter	31.7 (5–77)
With catheter and tube graft	64.1 (5–121)
Perfused ICAs/pt, *n* (range)	2.3 (1–4)
Reimplanted ICAs/pt, *n* (range)	2.5 (0–4)
Open proximal anastomosis, *n* (%)	5 (33)
CSF drainage, *n* (%)	10 (67)
MEP monitoring, *n* (%)	12 (80)

CSF, cerebrospinal fluid; MEP, motor evoked potential.

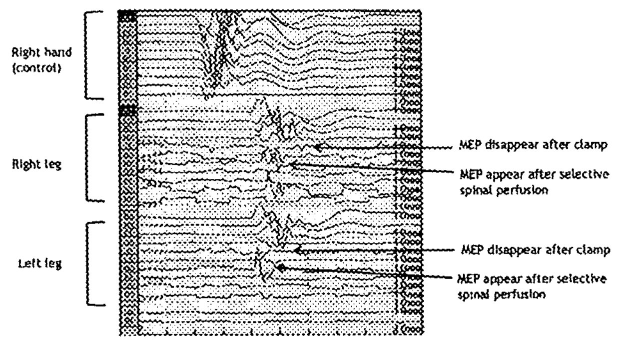

Fig. 4. MEPs were not observed in two patients directly after aortic cross-clamp. The changes of MEPs amplitude after cross-clamp were recovered by selective intercostal arteries perfusion.

3.3. *Morbidity and mortality*

There was no early mortality. There were no paraparesis/paraplegia, bleeding complications requiring reoperation, and postoperative renal insufficiency. All patients were discharged ambulatory.

4. Discussion

Postoperative paraplegia and paraparesis are devastating complications of DTA or TAAA repair. These pose not only the present physical disability but also a higher mortality rate among patients [1]. Repair of DTA or TAAA is a meticulous procedure, such as that a large number of segmental intercostal and lumbar arteries providing spinal cord perfusion may be disrupted, especially in patients with more extensive aneurysms. The presence of paraplegia immediately upon emergence from anesthesia suggests that an irreversible ischemic injury to the spinal cord occurred, perhaps related to the interruption of its vascular supply.

Spinal cord injury generally happens during temporary or permanent interruption of spinal cord blood supply. The pathophysiology of spinal cord injury in DTA or TAAA surgery is essentially an ischemia-infarction model. Thoracic aortic clamping reduces arterial blood supply to the spinal cord, increases spinal fluid pressure [7], and produces inadequate tissue oxygen delivery and ischemia [8]. Reperfusion after ischemia can further damage neuronal cells [9].

We have previously demonstrated the usefulness of preoperative detection of the intercostal artery supplying the Adamkiewicz artery for the reduction of the incidence of ischemic injury of the spinal cord [4]. This procedure establishes the best operational strategy for descending thoracic aortic aneurysm or TAAA repair. Surgical repair can be performed while the intercostal and lumbar arteries can be revascularized at or near the level of Adamkiewicz artery; thereby, spinal cord injury can be reduced. In our institute, we have routinely reconstructed or preserved an intercostal artery that may be related to the preoperatively detected Adamkiewicz artery during repair of thoracoabdominal or descending thoracic aortic aneurysm. However, even when the important segmental artery is successfully preserved, transient ischemia may occur during reimplantation, and thus cause spinal cord injury. Maintaining blood pressure within the aortic segment isolated by double cross-clamping has been shown experimentally to improve spinal cord blood flow [10].

We have previously reported that many patients do not have spinal cord ischemia even if the internal artery to Adamkiewicz artery is occluded after endovascular stent-graft repair [11]. Endovascular repair avoids aortic cross-clamping and may significantly decrease perioperative complications because of the minimally invasive nature of the procedure, avoidance of ischemia/reperfusion, and the associated changes in hemodynamics that occur during proximal aortic cross-clamping. In other words, patients are still at risk for paraplegia/paraparesis whether the procedure involves no aortic cross-clamping or no open aortic aneurysm, even if the intercostal artery to Adamkiewicz artery is occluded after endovascular stent-graft repair. It seems that the intercostal artery supplying the Adamkiewicz artery is not solely responsible for the total blood flow quantity to the spinal cord.

We believe that no single artery is so important in many patients, but rather it is the total amount of blood flow through all intercostal and lumber arteries or vertebral arteries from the subclavian artery or pelvic vascular plexus that determines adequacy of spinal cord perfusion during operation. However, dependence on the Adamkiewicz artery for the total amount of blood flow to the spinal cord is a reality in a patient.

Based on the above-mentioned theory, we attempted to perfuse the intercostal arteries mainly on the Adamkiewicz artery for the purpose of maintaining spinal cord perfusion pressure during the cross-clamping of the aorta. By this technique, total blood flow quantity in the spinal cord becomes equal to or more than a certain constant level. Below the constant level, patients will suffer spinal cord ischemia.

MEP changes during the cross-clamping of the aorta have been used to evaluate spinal cord perfusion pressure. The observed changes in MEPs indicate that selective perfusion of the segmental arteries was not sufficient to maintain adequate spinal perfusion. We experienced cases in which MEP amplitude disappeared after open aneurysm, but recovery of the amplitude after perfusion to the intercostal arteries was noted. MEPs are known to be very sensitive to spinal cord ischemia [12] and MEP changes clearly overpredict the number of ICAs that must be reimplanted to prevent infarction.

Safi and colleagues [13] determined that a lack of segmental arterial reattachment at various thoracolumbar levels resulted in specific early or delayed deficits. Jacobs and associates [14] used MEP changes to indirectly evaluate segmental spinal cord blood supply; in which they contended that a diffuse collateral network provided spinal cord blood supply in those with degenerative TAAAs. Wong and colleagues [15] suggested that reattaching a greater number of segmental arteries increased the likelihood of maintaining this rich collateral network. These papers show that it is very important to maintain total blood flow quantity from the intercostal and lumbar arteries or vertebral arteries or pelvic vascular plexus and other collateral arteries.

Many surgeons think that distal perfusion prevents spinal cord ischemia in an operation of DTA or TAAA. We think that perfusion to the intercostal arteries is the same as the