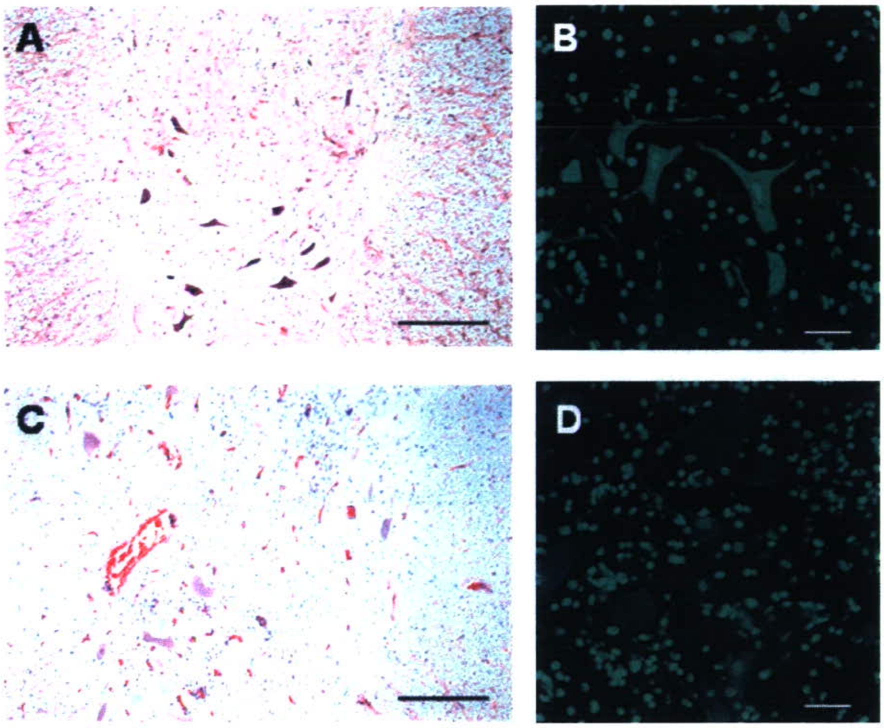

Figure 4. Representative photomicrographs of anterior horn of spinal cord sections. *A,* Section from group A stained with hematoxylin and eosin (*bar* represents 250 μm). Photomicrograph demonstrates a normal appearance. *B,* Section from group A after fluorescent Nissl staining (*bar* represents 50 μm). Nissl granules were clearly seen in large motor neurons. *C,* Section from group B stained with hematoxylin and eosin. Photomicrograph demonstrates severe, extensive gray matter necrosis (*bar* represents 250 μm). *D,* section from group B after fluorescent Nissl staining. Nissl granules were not identified in shrunken motor neurons (*bar* represents 50 μm).

neurons showed acute necrotic changes. Degenerating neurons were swollen or shrunken.

Significantly, a greater number of large motor neurons could be seen in the gray matter of all segments in group A than in corresponding segments in group B. Mean total number of intact motor neurons was significantly greater in group A (24.5 ± 6.8) than in group B (9.9 ± 6.8, $P = .0001$).

Discussion

To decrease invasiveness of catheter introduction, we redesigned the cooling catheter to contain a closed circuit passing through it in a countercurrent manner. The catheter is small enough to be placed with a minimally invasive procedure, which is an advance over the larger U-loop catheter used in our previous report. Furthermore, we also used thoracic aortic double crossclamping for 45 minutes, whereas we had made only single aortic crossclamping for 30 minutes in our previous study. We believe that our cooling method has proved to be an additional protective measure against ischemic spinal cord injury in a situation similar to that of clinical aortic surgery. We believe that the changed shape of the catheter may represent significant progress toward accomplishing the percutaneous introduction.

The bones and ligaments of the spinal canal produce less heat than muscle and abdominal organs. Aided by this unique physiologic anatomy, our small cooling catheter could cool the spinal cord selectively, effectively, and continuously. We induced mild systemic hypothermia of 36°C with a cooling–warming blanket and maintained the temperature during surgery, changing the blanket mode (cooling or warming) according to the situation. In pigs, under normothermic conditions (38°C), 45 minutes of double thoracic aortic clamping without distal perfusion induces metabolic acidosis as a result of severe ischemia of the abdominal organs and lower limbs, which often leads to death.

From the standpoint of thermal kinetics, the spinal cord, like other organs has three major sources of heat.

First is incoming blood flow, which carries not only oxygen and glucose but also heat. Second is the surrounding bone and connective tissue, which provides some insulation as mentioned previously but still produces and transmits some heat to the spinal cord by heat conduction. Third is the spinal cord itself, which produces heat biochemically by its own metabolism. When the spinal cord is cooled with an epidural catheter, an equilibrium develops involving balance between the amount of heat removed by proximity to the cooling catheter and heat from these three sources.

In our experimental group cooled by the epidural cooling system, sSEP disappearance after clamping occurred later than in the control group, and the regionally cooled pigs fully regained essentially baseline sSEP characteristics immediately after release of the clamp. Accordingly, the total time of sSEP loss was significantly longer in the control group than in the cooling group. Our neurologic results in this experimental study were consistent with the clinical observations of Grabitz and coworkers.[13] Monitoring of the sSEPs surveys conduction of impulses from afferent nerves as they ascend in the posterior column.[14] Axons are considered more resistant to ischemic stress than are neuronal cell bodies, particularly in the motor system.[15] Forty-five minutes of ischemia may not be long enough for all axons to lose function; however, such time might be sufficient for neuronal cell bodies to initiate irreversible processes leading to neuronal death.[16]

In a model of aortic double clamping, we demonstrated that our newly designed catheter could protect the spinal cord against ischemia for as long as 45 minutes. Because pigs are considered to show less tolerance than human beings of spinal cord ischemia, spinal cord protection against ischemic stress induced by 45 minutes of aortic double clamping in swine indicates considerable promise for efficacy in the clinical setting.

In clinical surgery, systemic moderate hypothermia induced by distal perfusion from the left atrium is commonly used. This lowers the temperature of the blood flow into the spinal cord, and additional use of our local cooling might further decrease the temperature of the spinal cord during aortic crossclamping, leading to more protection against spinal cord injury.

Clinically, sSEPs and motor evoked potentials are frequently monitored.[17] As long as the temperature of spinal cord is kept above 25°C, sSEPs and motor evoked potentials do not disappear as a result of the combined hypothermia and thus still could be a good indication of ischemic stress on the spinal cord.

Because our cooling catheter does not increase intrathecal pressure, the combination with cerebrospinal fluid drainage with another catheter into intrathecal space may lower the cerebrospinal fluid pressure during aortic crossclamping. The combined use may be a promising strategy to prevent paraplegia.

Drawbacks of our method include requirements for a small skin incision and a single-level laminectomy to place the cooling catheter. Further refinements of catheter introduction may permit wholly percutaneous placement in a fashion similar to introduction of a catheter for epidural anesthesia.

In conclusion, we have demonstrated in pigs that a newly designed catheter could cool the spinal cord to 9.7°C below the rectal temperature during double aortic crossclamping, without elevating cerebrospinal fluid pressure. Protective effects against ischemic spinal cord injury have been shown. We believe that our epidural cooling catheter may become a practical aid in avoiding paraplegia associated with aortic surgery, especially when used in combination with other protective techniques.

We express special thanks to Masanori Yoshida, PhD, Ryoichi Tashiro, PhD, Takashi Kimura, Shinobu Negishi, Ryota Wada, Norio Koike, Tatsuya Takagi, Yusuke Matsuda, Shinji Matsuo, and Setsuko Misawa for their technical assistance.

References

1. Svensson LG, Crawford ES, Hess KR, Coselli JS, Safi HJ. Experience with 1509 patients undergoing thoracoabdominal aortic operations. *J Vasc Surg.* 1993;17:357-70.
2. Cambria RP, Davison JK, Zannetti S, L'Italian G, Atamian S. Thoracoabdominal aneurysm repair: perspectives over a decade with the clamp-and-sew thchnique. *Ann Surg.* 1997;226:294-305.
3. Coselli JS, LeMaire SA, Conklin LD, Köksoy C, Schmittling ZC. Morbidity and mortality after extent II thoracoabdominal aortic aneurysm repair. *Ann Thorac Surg.* 2002;73:1107-15.
4. Griepp RB, Ergin MA, Galla JD, Lansman S, Khan N, Quintana C, et al. Looking for the artery of Adamkiewicz: a quest to minimize paraplegia after operations for aneurysms of the descending thoracic and thoracoabdominal aorta. *J Thorac Cardiovasc Surg.* 1996;112:1202-15.
5. Crawford ES, Coselli JS, Safi HJ. Partial cardiopulmonary bypass, hypothermic circulatory arrest, and posterolateral exposure for thoracic aortic aneurysm operation. *J Thorac Cardiovasc Surg.* 1987;94:824-7.
6. Kouchoukos NT, Masetti P, Rokkas CK, Murphy SF. Hypothermic cardiopulmonary bypass and circulatory arrest for operations on the descending thoracic and thoracoabdominal aorta. *Ann Thorac Surg.* 2002;74:S1885-8.
7. Rokkas CK, Cronin CS, Nitta T, Helfrich LR, Lobner DC, Choi DW, et al. Profound hypothermia for spinal cord protection in operations on the descending thoracic and thoracoabdominal aorta. *Semin Thorac Cardiovasc Surg.* 1998;10:57-60.
8. Tabayashi K, Niibori K, Konno H, Mohri H. Protection from post-ischemic spinal cord injury by perfusion cooling of the epidural space. *Ann Thorac Surg.* 1993;56:494-8.
9. Cambria RP, Clouse WD, Davison JK, Dunn PF, Corey M, Dorer D. Thoracoabdominal aneurysm repair: results with 337 operations performed over a 15-year interval. *Ann Surg.* 2002;236:471-9.
10. Meylaerts SA, Kalkman CJ, Haan P, Porsius M, Jacobs MJ. Epidural versus subdural spinal cord cooling: cerebrospinal fluid temperature and pressure changes. *Ann Thorac Surg.* 2000;70:222-7.
11. Mori A, Ueda T, Hachiya T, Kabei N, Okano H, Yozu R, et al. An epidural cooling catheter protects the spinal cord against ischemic injury in pigs. *Ann Thorac Surg.* 2005;80:1829-34.

12. Johnson MR, Tomes DJ, Treves JS, Leibrock LG. Minimally invasive implantation of epidural spinal cord neurostimulator electrodes by using a tubular retractor system. *J Neurosurg*. 2004;100:1119-21.
13. Grabitz K, Sandmann W, Stuhmeier K, Mainzer B, Godehardt E, Ohle B, et al. The risk of ischemic spinal cord injury in patients undergoing graft replacement for thoracoabdominal aortic aneurysms. *J Vasc Surg*. 1996;23:230-40.
14. Galla JD, Ergin MA, Lansman SL, Cullough JN, Nguyen KH, James DS, et al. Use of somatosensory evoked potentials for thoracic and thoracoabdominal aortic resection. *Ann Thorac Surg*. 1999:67:1947-52.
15. Lips J, Haan P, Bouma GJ, Jacobs MJ, Kalkman CJ. Delayed detection of motor pathway dysfunction after selective reduction of thoracic spinal cord blood flow in pigs. *J Thorac Cardiovasc Surg*. 2002;123:531-8.
16. Sakurai M, Hayashi T, Abe K, Sadahiro M, Tabayashi K. Delayed and selective motor neuron death after transient spinal cord ischemia: a role of apoptosis? *J Thorac Cardiovasc Surg*. 1998:115;1310-4.
17. Strauch JT, Lauten A, Spielvogel D, Rinke S, Zhang N, Weisz D, et al. Mild hypothermia protects the spinal cord from ischemic injury in a chronic porcine model. *Eur J Cardiothorac Surg*. 2004:25:708-15.

心臓外科医と技士で行う人工心肺の安全対策

冨澤康子　百瀬直樹　又吉　徹
四津良平　髙本眞一*

はじめに

人工心肺中の事故は重大な結果をもたらす．予想される人工心肺の事故の種類，その防止策，発生したトラブルの対処法をあらかじめ知らなければ，起きてしまった事故の対処はできない．事故は一定の確率で起き，突発的・瞬時に異常事態は発生する．経験を積み，トラブルなく日常の症例をこなしている体外循環技術認定士でさえ，訓練していなければトラブル発生時に手は動かない[1]．

2006年の第59回日本胸部外科学会定期学術集会にてハンズオンセッション「人工心肺コース」として，心臓外科医と技士が一緒に参加する人工心肺のトラブル対処の講習が行われた．そのときのアンケート結果から人工心肺の安全対策を考えたい．

I．対象および方法

基本的に心臓外科医とその体外循環を担当している技士を1組とし，30組をホームページで募集した．参加申し込みは30施設から計74名あった．講習では，2006年に作成した人工心肺トラブル対処のDVD[2]を供覧し，コーステキスト[3]を配布した．内容は4種類の典型的なトラブル，①体外循環終了後の再循環スタート→急速充填，②送血ポンプの故障（停電）→送血の復旧，③脱血のエアブロック→脱血回路の満たし方，④空気の誤送→回路・患者からの気泡除去，他を予定した．5台の人工心肺装置を用い，安全装置は日本体外循環技術医学会（JaSECT）が必須あるいは推奨しているSVo_2，レベルセンサー，回路内圧測定（人工肺前後），気泡検出器，動脈フィルター，一方向弁付きパージライン，安全弁付きベント回路を装着した．指導教官はJaSECTの技士があたった．アンケートを1施設2部の計60部配布し，終了時に回収した．回収率は100％であった．回答者の職種は心臓外科医27名（45%），臨床工学技士33名（55%）であった．回答者にはならなかったが，麻酔科医が1名参加していた．

II．アンケート回答の集計

人工心肺操作経験は医師の10名（37%）にあり，中央値10（4～100）例であった（図1）．それぞれの施設における2005年の体外循環例数は中央値70（15～300）例で，技士の生涯経験症例数は中央値100（20～1,500）例であった．

「体外循環担当者は体外循環技術認定士であるべきである」と医師の63%が答えたが，医師3

キーワード：人工心肺，安全対策，トラブルシューティング，体験学習

* Y. Tomizawa：東京女子医科大学心臓血管外科；N. Momose（副技師長）：自治医科大学大宮医療センター臨床工学部；T. Matayoshi（課長）〈医用工学センター〉，R. Yozu（教授）〈心臓血管外科〉：慶應義塾大学；S. Takamoto（教授）：東京大学心臓外科．

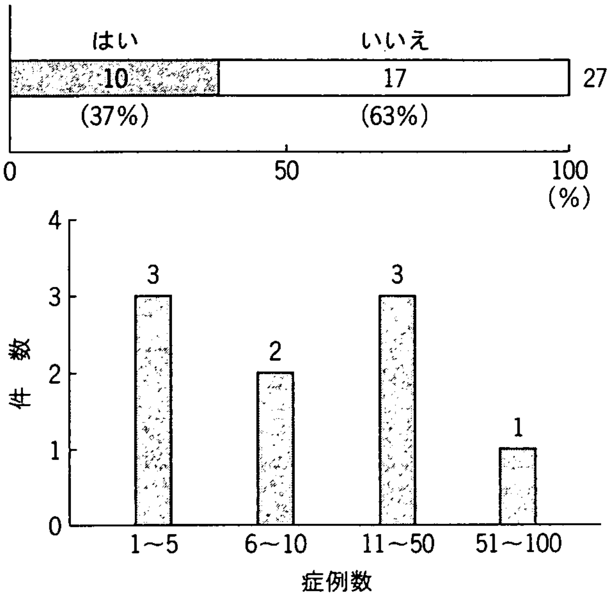

図 1．医師への質問「臨床で人工心肺を操作したことがありますか？」
はいの場合：その症例数　27.8±32.9（中央値 10，最小 4，最大 100）［回答数：9］

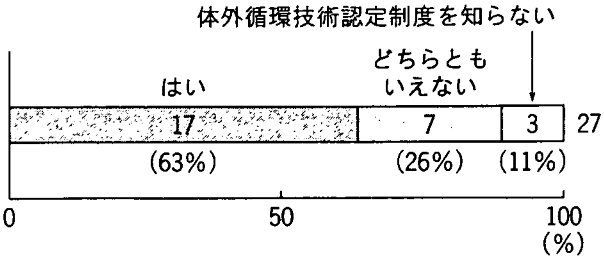

図 2．医師への質問「体外循環担当者は体外循環技術認定士であるべきですか？」

名（11%）は制度を知らなかった（図 2）．人工心肺の安全装置を購入する場合の障害は，医師および技士ともに「予算が取りにくい」が 67%ともっとも多く，2 番目に「安全装置が高額である」との回答であった（図 3）．安全装置の購入の障害に対して，医師からは「とくに障害はない」と「保守的なため理解がない」，技士からは「使用頻度と金額が折り合ない」と，「安全対策への理解が少ない」などの意見があった．安全装置の必要性を感じていないと答えた認定士資格のない技士 2 名のうち 1 名は，安全装置の必要性を感じていないにもかかわらず，「安全対策に熱心なのは技士だ」と回答した．またもう 1 名は安全装置の必要性を感じていなかったが，「本講習に参加して，必要だと思った」と回答した．この技士は「医師のすすめにより参加し，すべてのシミュレーションがむずかしく思え，手が動かなかった」と答えた．

「人工心肺の安全対策に熱心なのは」の問いに，医師も技士も同様に一番に技士を選び，次が心臓外科医であった（図 4）．技士から病院管理者が熱心との回答は皆無であり，2 名しか麻酔科医が熱心であると答えなかった．

トラブルのシミュレーション・トレーニングを行っているかの問いに，「常時」という回答は皆無であり，「今回がはじめて」と答えたのが医師 88%，技士 67%であった．「ときどき」と答えたのは医師 3 名，技士 11 名で，その頻度は医師平均 0.8（0.3～1）回/年，技士平均 1.6（0.5～4）回/年であった．「ときどき」と答えた医師は 3 名ともに「今回の経験を生かせる機会があればまた参加したい」と答えた．

「どのシミュレーション操作がむずかしかったか」の問いには，医師も技士も半数が空気誤送を選択し，3 割がポンプ故障の対処をあげた（図 5）．「想像していたように操作ができた」と答えたのは医師 1 名，技士 9 名のみであった．「思ったより手が動かなかった」と医師の 96%，技士の 71%が答えた．その他，医師から「ハンドクランクの場所がわからなかった」，「全然手が動かなかった」，技士から「ポンプ側の対応はできるが，術者や麻酔科医との連携がむずかしかった」，「今起きている状況がどうなのかを瞬時に判断できなかった」，「（トレーニングなのに）頭が真っ白になりかけた」などの感想があった．

「今回のハンズオンセッションは有意義であったか」の問いに，技士は全員，医師も 93%は「有意義だった」と答えた．「ある程度ためになったと」答えた医師が 2 名いたが，うち 1 名は「100 例の臨床操作経験があり，トラブルトレーニングを年に 1 回行っている」と答えた．

今回体験したことで「実際のトラブルに対してこの経験が生かせると思うか」の問いに，医師は全員，技士は 1 名を除いて「はい」と答えた．「いいえ」と答えた技士の 1 名は，「よい経験でふたたび参加したいが，もっと訓練が必要である」と答えた．「今後も機会があれば参加したいか」の問いに，1 名を除いて医師も技士も「はい」と答えた．「いいえ」と答えた医師は昨年の症例数

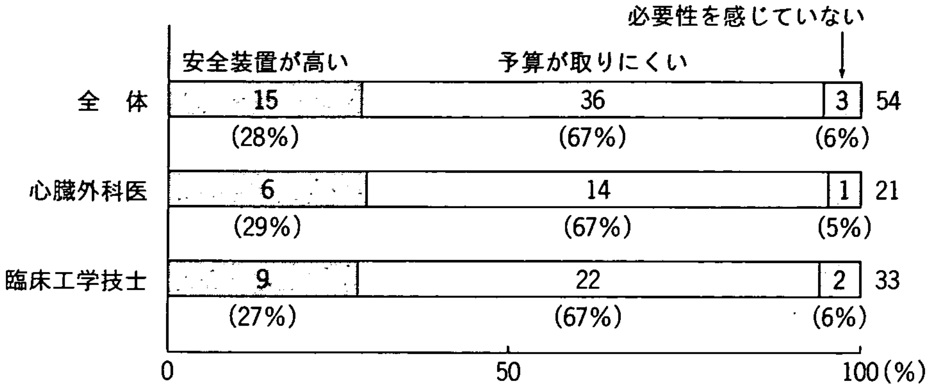

図 3. 「あなたの施設で人工心肺の安全装置を購入する場合の一番の障害は？」（複数回答）

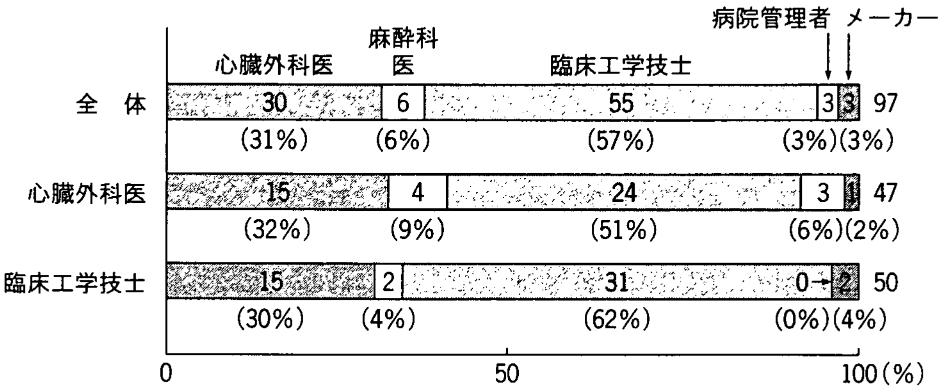

図 4. 「あなたの施設で人工心肺の安全対策に熱心なのは？」（複数回答）

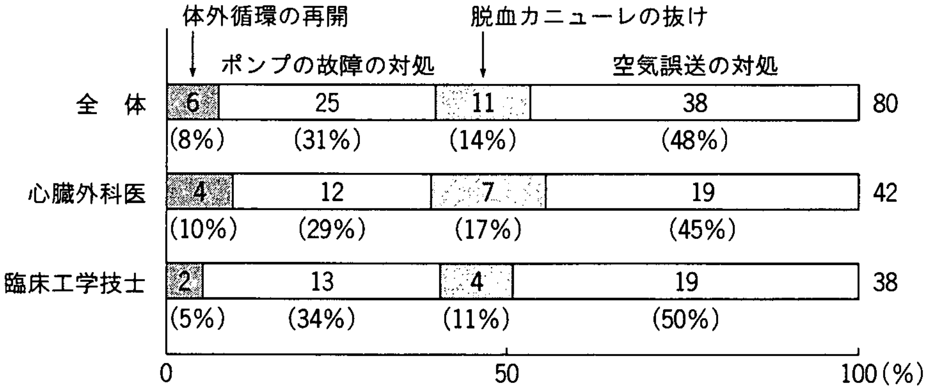

図 5. 「どのシミュレーション操作がむずかしかったですか？」（複数回答）

50 例の施設からの参加で，臨床操作経験が 20 例あり，「自分ばかりでなく同じ施設の主に術者になる医師を含めて参加すべきである」と述べた．

自由記載では，医師は「人工心肺をまわしたことのない心臓外科世代として，今回の経験は非常に勉強になった」，「必ず医師と ME で参加するのがよい」，技士は「医師と一緒に勉強できてよかった」という意見を述べてあった．

Ⅲ. 考　察

人工心肺を用いた体外循環には以下の特徴がある．① 術式に応じて多様な装置と技術が用いられる，② 使用する材料が多く，組み合せが多い，③ 事故は瞬時に起る，④ 事故が起きたら短時間で，手持ちの機材で，その場にいる者で対処しなくてはならない，⑤ 対処方法は状況により異な

る，⑥事故が起ればしばしば致命的となる，あるいは重篤な後遺症を残す．

近年，体外循環操作時の安全装置およびセンサー類の使用を含む安全対策は，より細部にまで求められる傾向にある[4]．それにもかかわらず，マニュアルなどの活用状況および安全監視装置の設置状況は欧米に比べて低い[5]．古瀬らの調査[5]では，人工心肺危機対策マニュアルは15%の施設，貯血槽のレベルセンサーは58%，送血ポンプの気泡センサーは20%の施設でしか利用されていなかった．

本企画は，臨床において体外循環の操作経験のない医師を中心に考え，プログラムを作成した．医師と一緒に臨床経験豊富な技士が多数参加していたが，回答したすべての技士がこのハンズオンセッションは有意義であり，さらに今後も機会があれば参加したいと答えた．すなわち，分業化のすすんだ世代の心臓外科医が，技士と一緒にトラブル対処の体験学習に参加して学んだばかりでなく，技士も体外循環における医療連携，安全装置の最近の使用方法，他施設の安全対策を学ぶよい機会であったことが示唆された．

操作のむずかしさでは，医師・技士ともに複雑な鉗子操作を必要とする空気誤送の対処を一番に，ポンプの手動操作自体は単純であるがポンプの故障への対処を二番にあげた．体外循環中の緊急事態発生時の対応を，日頃の訓練により確保できることを認識したはずである．

施設ごとに回路構成を含む体外循環システム，人的要素および環境は異なる．そのため本企画では練習の場を設けただけではなく，体外循環の安全に対する意識を高める機会になることをめざした．人工心肺事故では発生時の状況判断と発生後の問題解決能力が重要である．自施設のシステムで，年に1回以上は体外循環担当者のみならず心臓外科医も参加するトラブル対処のトレーニングを行い，医療連携を確認する機会をもつべきである．

近年，体外循環操作が分業化される傾向にあるが，体外循環の知識と技術に優れた体外循環技術認定士を病院組織は完全には活用しておらず[6]，マニュアル類の不備や安全装置の未装備で安全対策に遅れのある施設がまだ多数存在することが指摘されている[7]．人工心肺事故を減らすために，医療従事者は今後もこのようなトラブル対処の講習会に積極的に参加し，安全な体外循環操作に努めてほしい．

おわりに

心臓外科医は人工心肺を用いた体外循環の安全を「技士任せ」にせず，関係する講習会から知識を補い，基本的な訓練を行い，臨床ではマニュアル類の整備，監視装置の活用により安全性を確保し，自施設の体外循環の安全を高めることに一層努力すべきである．

指導教官を務めてくださった日本体外循環技術医学会の皆様，および装置・機器にご配慮くださった泉工医科工業㈱，テルモ㈱，ソーリン㈱，トノクラ医科工業㈱，㈱JMSの方々に感謝する．

文　献

1）冨澤康子，四津良平，百瀬直樹ほか：体外循環を安全に行うためのシミュレーション教育―体外循環のトラブルシミュレーション―ウエットラボの経験．人工臓器 **35**：233-236, 2006

2）日本人工臓器学会/教育・臨床工学委員会：人工心肺の基本操作とトラブル対処法 1（DVD），日本人工臓器学会/教育・臨床工学委員会，東京，2006

3）冨澤康子：人工心肺を用いた体外循環に関する心臓外科医の安全対策．胸部外科 Up to Date 2006，高本眞一（編），p200-205, 2006

4）冨澤康子：人工臓器は開発の時代から使用時の安全をより考える時代に．人工臓器 **34**：129-130，2005

5）人工心肺の安全マニュアルに関する研究班［古瀬　彰］：医療における危険領域のリスク分析とフェイルセーフシステムに関する研究-分担研究「人工心肺の安全マニュアル作成に関する研究」報告書．平成14年度厚生科学研究，2003

6）Tomizawa Y, Momose N：Certified perfusionist in Japan. J Artif Organs **10**：122-123, 2007

7）見目恭一：人工臓器―最近の進歩―体外循環技術．人工臓器 **34**：210-214, 2005

SUMMARY

Safety Measures of Extracorporeal Circulation by Heart Surgeons and Perfusionists

Yasuko Tomizawa et al., Department of Cardiovascular Surgery, Tokyo Women's Medical Univercity, Tokyo, Japan

In the past, heart surgeons often set up the extracorporeal circulation (ECC) system, primed the circuit, and operated the ECC in Japan. As works of perfusionists recently became specialized, young Japanese heart surgeons seldom receive education on ECC, and rarely operate ECC. ECC accidents are rare, but once it occurs, even a well experienced perfusionist often becomes too upset to think of the next action, while surgeons at the operative table have little knowledge of the ECC system. Reconsideration of ECC education for heart surgeons is still rare. As a medical team, tragedies such as death and life-threatening complication due to an ECC accident are to be prevented at all costs. At an on-site training session for ECC troubles at the 59th annual meeting of Japanese Association for Thoracic Surgery, the basic ECC operations, recovering procedures after an accident, and the use of safety devices were taught to 30 teams of young heart surgeons and perfusionists as a measure to ensure safety of ECC. A questionnaire survey was conducted at the end and satisfactory results were obtained.

KEY WORDS

extracorporeal circulation/safety measures/troubleshooting/on-site training

* * *

Stress distribution on the thorax after the Nuss procedure for pectus excavatum results in different patterns between adult and child patients

Tomohisa Nagasao, MD, PhD,[a] Junpei Miyamoto, MD,[a] Tamotsu Tamaki, PhD,[b] Kazuhiko Ichihara, MD, PhD,[c] Hua Jiang, MD, PhD,[d] Toshihiko Taguchi, MD, PhD,[c] Ryohei Yozu, MD, PhD,[e] and Tatsuo Nakajima, MD, PhD[a]

Dr Nagasao

Objective: In the Nuss procedure, in which the deformed thorax is forcibly corrected by insertion of correction bars, considerable stresses occur on the patient's thorax. We performed the present study to elucidate how stress patterns on the thorax after this procedure differ between child and adult patients.

Methods: Eighteen patients with pectus excavatum, constituting a child group (n = 10) and an adult group (n = 8), were included in the study. After a 3-dimensional computer-assisted design model was produced with computed tomographic data from each patient, simulation of the Nuss procedure was performed on the model. Then the stresses occurring on each thorax were calculated using the finite element method. The stresses were compared between the child and adult groups in terms of intensity on each rib and the distribution patterns over the whole thorax.

Results: With all 12 ribs, significantly greater stress occurred in the adult group than stress in the child group. Although the stresses occurring on the thorax demonstrated concentrated patterns in the child group, widely distributed patterns were observed in the adult group.

Conclusions: The stresses that occur on the thorax after the Nuss procedure take different patterns between children and adults in terms of intensity and distribution. The differences should be taken into consideration in managing postoperative pain after the Nuss procedure.

From the Departments of Plastic and Reconstructive Surgery[a] and Cardiovascular Surgery,[e] School of Medicine, Keio University, Tokyo, Japan; the Nippon Institute of Technology,[b] Saitama, Japan; the Department of Orthopedics,[c] School of Medicine, Yamaguchi University, Yamaguchi, Japan; and the Department of Plastic and Reconstructive Surgery,[d] ChangZheng Hospital, Second Military Medical University, Shanghai, China.

Received for publication May 19, 2007; revisions received July 24, 2007; accepted for publication Aug 16, 2007.

Address for reprints: Tomohisa Nagasao, MD, PhD, Department of Plastic and Reconstructive Surgery, Keio University Hospital, Shinjuku-Ward Shinanomachi 35 Tokyo, Japan (E-mail: nagasao@sc.itc.keio.ac.jp).

J Thorac Cardiovasc Surg 2007;134:1502-7

0022-5223/$32.00

doi:10.1016/j.jtcvs.2007.08.013

The Nuss procedure brought innovation to surgical treatment of pectus excavatum.[1-5] This procedure is advantageous in its reduced invasiveness and technical ease.[6-12] Because of its feasibility, some institutes use the Nuss procedure as the first-choice treatment option for pectus excavatum.[13] Although the Nuss procedure is useful, it also has its disadvantages—in particular, postoperative pain. Because the sunken sternum and costal cartilages are forcibly elevated by means of insertion of correction bars, considerable stresses occur on the thorax, often causing a great deal of postoperative pain. It is important to understand the stress occurrence pattern on the thoraces undergoing operation to alleviate the postoperative pain. We conducted the present study to elucidate the intensity and distribution patterns on thoraces after the Nuss procedure.

Materials and Methods

Production of Thorax Computer-assisted Design Models

Collection of computed tomographic data. We collected computed tomographic (CT) data of 18 patients with pectus excavatum. We classified the patients into 2 groups based on their ages. Patients younger than 11 years were included in the child group. Patients older than 20 years were included in the adult group. The average ages of the child group (n = 10, 7 male and 3 female patients) and of the adult group (n = 8, 6 male and 2 female

Abbreviations and Acronyms

CAD = computer-assisted design
CT = computed tomographic
FEM = finite element method

patients) were 7.4 ± 2.5 years and 26.8 ± 4.6 years, respectively. For all patients, informed consent was obtained to be included in the present study.

Computer-assisted design model production. Based on the CT data, we produced a computer-assisted design (CAD) model for each of the 18 patients, simulating the patient's thorax. First, we input the CT data into a workstation (Dell Inspiron 6000; Dell Co, Round Rock, Tex). Then, using graphic software (Rhinoceros 4.0; Applicraft Co, Tokyo, Japan), we extracted the data of the thorax part from the original CT data. Furthermore, we edited the data of the thorax by using structural analysis software (ANSYS10.0; ANSYS Co, Chicago, Ill) to produce a CAD model for each patient's thorax (Figure 1). To produce the CAD models, we simulated each of the 12 ribs, the sternum, and each of the 12 vertebrae by using 6, 18, and 36 beam elements, respectively. We simulated each of the costal cartilages by using different numbers of beam elements according to morphologic complexity. For the simulation of each of the first to fifth costal cartilages, 6th to 10th costal cartilages, and 11th to 12th costal cartilages, 5, 5 to 10, and 3 beam elements were used, respectively.

Simulation of the Nuss Procedure

We performed simulation of the Nuss procedure on each thorax CAD model. We conducted the simulation on the assumption that a correction bar was placed at the fourth intercostal space (Figure 2, *A*). For each thorax, we applied anterior-directed forces on the posterior aspect of the sternum until it reached the same anterior-posterior height as the points on the fifth rib, at which point the correction bar was supported (Figure 2, *B*). Under these dynamic conditions, we calculated the von Mises stresses that are expected to occur on the thorax by using the finite element method (FEM). We performed the calculation with the structural analysis program available in the software (ANSYS10.0). With the same calculation, we also modeled the corrected shapes of the thoraces (Figure 2, *C*). We obtained Young's moduli used in the calculation from the CT density of each patient with the methods of Kopperdahl and colleagues.[14] Kopperdahl and colleagues, after studying 45 vertebral bodies, demonstrated that a linear relationship exists between the quantitative CT density and Young's modulus in the vertebra. The relationship was presented by an equation, $E = -34.7 + 3230QCT$, where E and QCT indicate the Young's modulus (in megapascals) and CT density (in grams per milliliter). Assuming that this equation is applicable for the ribs, sternum, and costal cartilages, we calculated the Young's moduli of these thorax components using the quantitative CT density of the corresponding tissues for each patient. We show the Young's moduli obtained this way in Table 1. We used these Young's moduli for the simulation.

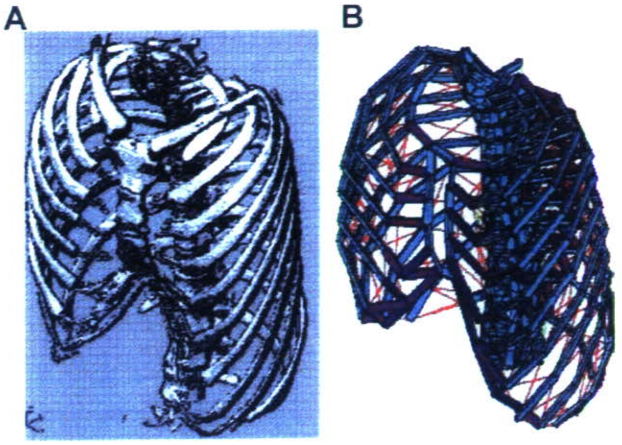

Figure 1. Based on the 3-dimensional computed tomographic data, we produced a computer-assisted design model for each patient. A, Three-dimensional computed tomographic image of a patient. B, Corresponding computer-assisted design model.

Evaluation

Intensity of the stresses. We compared the intensities of the maximum stresses occurring on each rib between the child and adult groups.

Stress distribution patterns. We compared the patterns in which the stresses were distributed on the thorax between the child and adult groups.

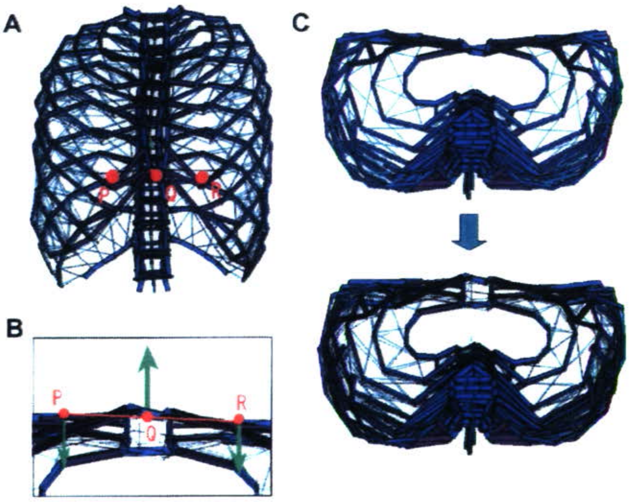

Figure 2. Simulation of the Nuss procedure. A, Three points were marked: at the edges of the bilateral fifth ribs (*P* and *R*) and at a point on the posterior aspect of the sternum *(Q)*. B, Assuming that a metal correction bar was inserted at the fourth intercostal space, we applied an anterior-directed force on Q. We also applied countering forces on P and R. We applied these forces until Q reached the segment between P and R. Thus the sternum was elevated to a height equivalent with P and R. C, Preoperative *(upper)* and postoperative shapes *(lower)* of a simulation model.

Verification of the Calculations' Validity

To verify the validity of the simulation, we compared the actual postoperative shapes of the thoraces with the simulation-expected postoperative thorax shapes of the corresponding CAD models. We conducted this verification on 4 patients in whom postoperative CT data were available. For each thorax, we marked points at 6 sites (the center of the sternum, the xiphoid process, and 4 points on the costal margin at which the costal cartilages intersect with the margin; Figure 3). We measured preoperative–postoperative locational changes at the 6 points by using three-dimensional medical imaging software (3D-Doctor; Able Software Co, Lexington, Mass). Thus for the 6 marking points of each thorax, we had 2 data sets of deviation values: the actually measured deviation values and the simulation-expected deviation values. We calculated correlation coefficients between the 2 data sets for each thorax. Thereby we confirmed the validity of the simulation.

Statistical Methods

For the comparison of the stresses between the child and adult groups, we used a nonparametric examination (Mann-Whitney *U* test) because the stresses showed skewed distributions. For the examination of the compatibility between actual operative results and results of simulation in the verification experiment, we calculated a correlation coefficient between the 2 data sets. All calculations were performed with SPSS Version 15 for Windows (SPSS, Inc, Chicago, Ill).

Results

Stress Intensity on Ribs

On all 12 of the ribs, significantly greater stresses occurred in the adult group than in the child group (Figure 4). The difference was statistically significant for each of the 12 ribs.

Stress Distribution Patterns

In the child group intensified stresses occurred only on the fifth rib, whereas intensified stresses occurred on the third to the seventh ribs in the adult group (Figures 4 and 5).

Compatibility of the Calculated and Measured Data

For the 5 cases, the correlation coefficients between the calculated and measured deviation data were 0.995, 0.995, 0.999, and 0.996, respectively. The nearness of these correlation coefficients to 1 demonstrates the validity of the simulation.

TABLE 1. Young's modulus for each component material

	Child group		Adult group	
	Median (kg/mm^2)	Range (kg/mm^2)	Median (kg/mm^2)	Range (kg/mm^2)
Cortical bone	1520	1440-1600	1750	1580-1920
Cancellous bone	150	140-160	180	160-200
Costal cartilage	1.2	0.8-1.6	88	62-104

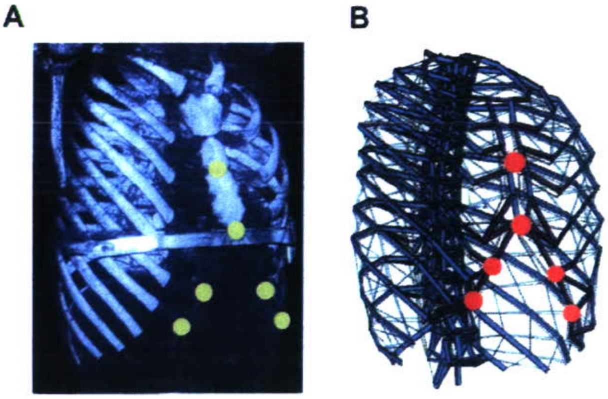

Figure 3. We confirmed validity of the simulation by comparing actual and calculated shapes of the thorax. A, Actual postoperative shape of a patient's thorax. We marked 6 points on the thorax *(yellow points)* to compare the displacements of the corresponding points (*red points* in B) of the corresponding computer-assisted design model. B, The corresponding computer-assisted design model.

Discussion

Nuss Procedure and Postoperative Pain

Pectus excavatum is the most common congenital chest wall deformity.[15] The deformity of the thorax in the pectus excavatum seriously affects the patients' psychologic conditions. Even worse, depressions of the thorax sometimes impair the patients' cardiopulmonary functions.[16] The Nuss procedure revolutionized treatment of pectus excavatum.[1] The procedure enabled surgical correction of the deformed thorax with inconspicuous wounds, short operating time, and easy technique.[17,18]

On the other hand, with all the advantages of the Nuss procedure, it is not without problems. Patients who undergo the Nuss procedure often experience intolerable chest pain during certain periods after the operation. In the Nuss procedure malpositioned costal cartilages, ribs, and sternum are forced to realign through the insertion of metal correction bars. Therefore, intensified stresses occur on the thorax, which causes the postoperative pain.

Methods

In the present study we used the FEM in elucidating the stresses occurring on the patients' thoraces. Because the methodologic reliability of FEM is already validated, it is used for biomechanical analyses of various organs.[19-24] However, because it is a theoretic method, we believe the validity of the FEM should be confirmed for each experiment. Based on this belief, we conducted verification of the present experiment by comparing the calculated and measured deviation at 6 points of 4 thoraces, with results

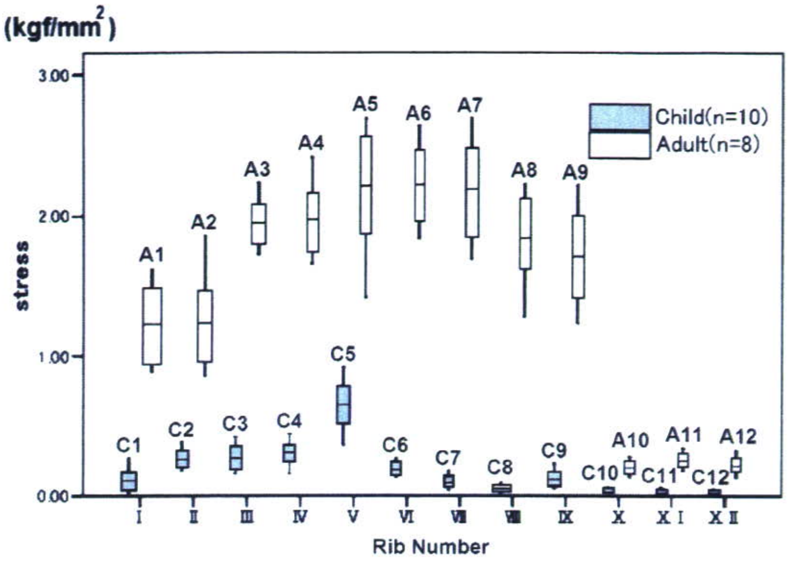

Figure 4. Box plots indicating postoperative stresses on each rib. Each box indicates the range in which 50% of the data are covered. The bars inside the boxes indicate the averages of the data. The letters on each box indicate the group and number of the rib (eg, A3 indicates the third rib for the adult group).

supporting the methodological correctness of the present experiment.

Findings and Their Clinical Meanings

Two findings were obtained in the present study. The first finding is that on all 12 ribs, greater stresses occur in adult patients than in child patients. The second finding is that in adult patients intensified stresses occur on plural ribs, whereas intensified stresses only occur on the bar-supporting rib (the fifth rib) in child patients. How do these findings contribute to clinical practices?

In our clinical experience we have perceived that adult patients are more likely to complain of pain than child patients after the Nuss procedure. The average times the patients in the present study took to become ambulatory were 2.3 ± 1.2 days for the child group and 5.1 ± 1.6 days for the adult group. The difference in tolerance to pain can be supported by the first finding. In adult patients greater stresses occur on the ribs than in those of child patients. Accordingly, greater pain is induced in adult patients than pain in child patients.

We have also perceived that adult patients tend to complain of pain in wider regions of the chest than do child patients. This perception is explained by the second finding. Because stresses as great as those occurring on the bar-supporting rib also occur on several neighboring ribs, the adult patients feel pain in a wide range of the thorax. We hypothetically attributed the cause of the second finding to the difference in the flexibility of the costal cartilages between children and adults (Figure 6). Because of the placement of the correction bar at the fourth intercostal space, the sternum is elevated in the anterior direction at this level. Naturally, the sternum is also elevated at other intercostal levels. Because the costal cartilages are attached to the sternum, they are pulled anteriorly as the sternum is elevated and are reshaped. In child patients the costal cartilages are rich in flexibility. Therefore, stresses occurring with the reshaping are absorbed by the costal cartilages. On the other hand, costal cartilages of adult patients are rigid because of age-related ossification. Because of this rigidity, the costal cartilages are less likely to bend according to the elevation of the sternum. Accordingly, the distortion stresses caused

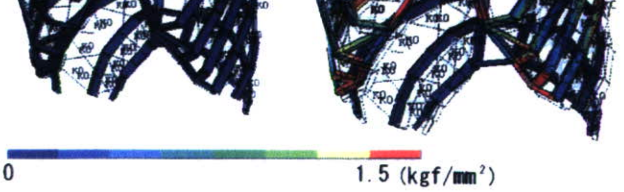

Figure 5. Examples of stress distribution patterns for the child and adult groups. A, In the child patients intensified stresses, although modest compared with those seen in adult patients, occurred only on the bar-supporting rib. B, In the adult patients intensified stresses occurred not only on the bar-supporting rib but also on other neighboring ribs.

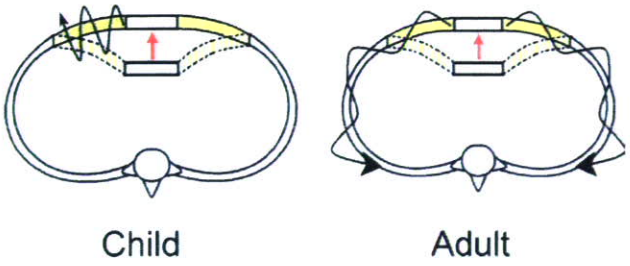

Figure 6. The authors' hypothetical explanation of the difference of stress occurrence patterns between child and adult patients. A, In child patients stresses caused by the forced elevation of the sternum are absorbed by the costal cartilages because of their flexibility. B, In adult patients the costal cartilages are rigid. Therefore, stresses caused by the elevation of the sternum are transmitted to the ribs without being absorbed by the costal cartilages.

by the sternum's elevation are transmitted to the ribs. Hence in adult patients intensified stresses occur on a wide range of ribs. Because of this wide stress distribution, the adult patients perceive pain in a wide region of the thorax. In performing the Nuss procedure, continuous application of local anesthetic is often conducted through epidural tubes inserted in the patient's back. The second finding suggests that different anesthetic considerations are necessary for child and adult patients. For child patients, it is enough to anesthetize only the bar-supporting rib, whereas for adult patients, it is necessary to extend the anesthetizing areas to include several ribs neighboring the bar-supporting rib.

Besides explaining the pain patterns, the findings of the present study can also be used in predicting the risks of recurrences.

The stresses demonstrated in the results are those occurring on the thoraces immediately after the operation. These stresses are expected to decrease as time passes because of the viscoelastic nature of the human body. However, considering the great difference in the stress intensity between the adult thoraces and child thoraces immediately after the operation, it is reasonable to speculate that the difference will remain even after the stresses decrease in a month-long or year-long period of time. The stresses occurring on the thoraces indicate the forcibility with which their shapes are corrected or the tendency for a thorax to recover its original shape. In other words, high stresses on a thorax indicate the risks of recurrence. Therefore on the condition that stresses on the adult thoraces are greater than those on the child thoraces after a certain period of time, we can assume that risks of recurrence are higher in adult patients than in child patients.

However, the validity of this speculation needs to be proved. With the authors' current analysis technique, we cannot quantitatively predict the stresses occurring on the thoraces in a month-long or year-long period after the operation. As an advanced study, time-related change of the stress on the thoraces should be investigated.

Originality of the Present Research

Some existing studies have taken a biomechanical approach in their analyses of pectus excavatum.[25] However, as far as we know, the present study is the first study that quantitatively elucidates stress distribution patterns on the thorax after the Nuss procedure. The authors believe that the findings of the present study help thoracic, cardiovascular, pediatric, and plastic surgeons with their performance of the Nuss procedure.

Conclusions

We conducted the present study to elucidate differences in stress occurrence patterns on the thorax between child and adult patients with pectus excavatum after the Nuss procedure. On all 12 ribs, greater stresses occur in adult patients than in child patients. Although intensified stresses occur only on the bar-supporting rib in child patients, intensified stresses also occur on other ribs in adult patients. These findings are helpful in managing postoperative pain after the Nuss procedure.

References

1. Nuss D, Kelly REJ, Croitoru DP, Katz ME. A 10-year review of a minimally invasive technique for the correction of pectus excavatum. *J Pediatr Surg.* 1998;33:545-52.
2. Hebra A, Swoveland B, Eqbert M, Taqqe EP, Georqeson K, Othersen HBJ, et al. Outcome analysis of minimally invasive repair of pectus excavatum: review of 251 cases. *J Pediatr Surg.* 2000;35:252-8.
3. Croitoru DP, Kelly REJ, Goretsky MJ, Gustin T, Keever R, Nuss D. The minimally invasive Nuss technique for recurrent or failed pectus excavatum repair in 50 patients. *J Pediatr Surg.* 2005;40:181-7.
4. Huang PM, Wu ET, Tseng YT, Kuo SW, Lee YC. Modified Nuss operation for pectus excavatum: design for decreasing cardiopulmonary complications. *Thorac Cardiovasc Surg.* 2006;54:134-7.
5. Schalamon J, Pokall S, Windhaber J, Hoellwarth ME. Minimally invasive correction of pectus excavatum in adult patients. *J Thorac Cardiovasc Surg.* 2006;132:524-9.
6. Ravitch MM. The operative treatment of pectus excavatum. *Ann Surg.* 1949;129:429-44.
7. Hawkins JA, Ehrenhaft JL, Doty DB. Repair of pectus excavatum by sternal eversion. *Ann Thorac Surg.* 1984;38:368-73.
8. Hayashi A, Maruyama Y. Vascularized rib strut technique for repair of pectus excavatum. *Ann Thorac Surg.* 1992;53:346-8.
9. Bentz ML, Rowe MI, Wiener ES. Improved sternal fixation in the correction of pediatric pectus excavatum. *Ann Plast Surg.* 1994;32:638-41.
10. Komuro Y, Masuda T, Kobayashi S, Yoza S, Ohmori K. Endoscopic correction of pectus excavatum. *Ann Plast Surg.* 1999;43:232-8.
11. Nakajima H, Chang H. A new method of reconstruction for pectus excavatum that preserves blood supply and costal cartilage. *Plast Reconstr Surg.* 1999;103:1661-6.
12. Chang PY, Lai JY, Chen JC, Wang CJ. Long-term changes in bone and cartilage after Ravitch's thoracoplasty: findings from multislice computed tomography with 3-dimensional reconstruction. *J Pediatr Surg.* 2006;41:1947-50.
13. Petersen C, Leonhardt J, Duderstadt M, Karck M, Ure BM. Minimally invasive repair of pectus excavatum—shifting the paradigm? *Eur J Pediatr Surg.* 2006;16:75-8.
14. Kopperdahl DL, Pearlman JL, Keaveny TM. Biomechanical consequences of an isolated overload on the human vertebral body. *J Orthop Res.* 2000;18:685-90.

15. Cartoski MJ, Nuss D. Goretsky MJ, Proud VK, Croitoru DP, Gustin T, et al. Classification of the dysmorphology of pectus excavatum. *J Pediatr Surg*. 2006;41:1573-81.
16. Grillo HC, Wright CD, Dartevelle PG, Wain JC, Murakami S. Tracheal compression caused by straight back syndrome, chest wall deformity, and anterior spinal displacement: techniques for relief. *Ann Thorac Surg*. 2005;80:2057-62.
17. Boehm RA, Muensterer, Till H. Comparing minimally invasive funnel chest repair versus the conventional technique: an outcome analysis in children. *Plast Reconstr Surg*. 2004;114:668-75.
18. Molik KA, Engum SA, Rescorla FJ, West KW, Scherer LR, Grosfield JL. Pectus excavatum repair: experience with standard and minimal invasive techniques. *J Pediatr Surg*. 2001;36:324-8.
19. Nagasao T, Nakajima T. Kimura A, Kaneko T, Jin H. Tamaki T. The dynamic role of "buttress" reconstruction after maxillectomy. *Plast Reconstr Surg*. 2005;115:1328-1341.
20. Nagasao T, Miyamoto J. Nagasao M. Ogata H, Kaneko T, Tamaki T. et al. The effect of striking angle on the buckling mechanism in blowout fracture. *Plast Reconstr Surg*. 2006;117:2373-81.
21. Scheltes JS, van Andel CJ, Pistecky PV, Borst C. Coronary anastomotic devices: blood-exposed non-intimal surface and coronary wall stress. *J Thorac Cardiovasc Surg*. 2003;126:191-9.
22. Grande-Allen KJ, Cochran RP, Reinhall PG, Kunzelman KS. Coronary anastomotic devices: blood-exposed non-intimal surface and coronary wall stress. *J Thorac Cardiovasc Surg*. 2003;126:191-9.
23. Remmler D, Olson L. Duke D, Ekstrom R, Matthews D, Ulrich CG. Presurgical finite element analysis from routine computed tomography studies for craniofacial distraction: II. An engineering prediction model for gradual correction of asymmetric skull deformities. *Plast Reconstr Surg*. 1998;102:1395-404.
24. Mizunuma M, Yanai A. Tsutsumi S, Yoshida H. Inoue M, Nishida M. Can dog-ear formation be decreased when an S-shaped skin resection is used instead of a spindle skin resection? A three-dimensional analysis of skin surgery techniques using the finite element method. *Plast Reconstr Surg*. 2000;106:845-51.
25. Weber PG, Huemmer HP, Reingruber B. Forces to be overcome in correction of pectus excavatum. *J Thorac Cardiovasc Surg*. 2006; 132:1369-73.

Surgical Techniques

Aortic Translocation with Autologous Tissue

Ryo Aeba, MD
Ryohei Yozu, MD

Aortic translocation, although technically demanding, could be an excellent surgical option for d-transposition of the great vessels and left ventricular outflow tract obstruction. We report a modification of the aortic translocation technique that uses autologous tissue. The aortic root is mobilized from the right ventricle with an extension of infundibular free-wall muscle for use in closure of the ventricular septal defect, which is similar to the technique for harvesting pulmonary autograft in the Ross-Konno procedure. Our modification may offer an even better surgical outcome for aortic translocation. ***(Tex Heart Inst J 2007;34:420-2)***

In the surgical management of d-transposition of the great vessels and left ventricular outflow tract (LVOT) obstruction, aortic translocation with biventricular outflow reconstruction may be superior to more conventional repairs such as the Rastelli and LeCompte operations, since the result more closely approximates the normal anatomy. Aortic translocation is accompanied by prosthetic patch repair of the ventricular septal defect (VSD), if the VSD is not too small and restrictive. Avoiding the use of any prosthetic material may offer an even better surgical outcome. We report a technical modification of the aortic translocation technique that uses autologous tissue.

Case Report

In April 2005, a 3-year-old boy who weighed 15 kg and had significant cyanosis was referred to our hospital for surgical repair of d-transposition, VSD, and LVOT obstruction. He had undergone 2 previous central shunt placements to alleviate severely hypoplastic arborization of the pulmonary artery. Preoperative cardiac evaluation with echocardiography and catheterization showed transposition of the great vessels {S,D,L} and a 1L-2RCx coronary pattern[1] (Fig. 1).

After heart re-exposure and takedown of the previous shunt, we established complete cardiopulmonary bypass with dual venous cannulation and instituted cardiac arrest. Upon opening the right atrium, we noted a conoventricular type of VSD (diameter, 25 mm) with an inlet extension. After division of the ascending aorta a few millimeters distal to the sinotubular junction, we mobilized the aortic root from the right ventricle together with an extension of infundibular free wall muscle, by means of a technique (Fig. 2) similar to pulmonary autograft harvesting in the Ross-Konno procedure. We took care to harvest the aortic root from the right ventricular free wall along a line that would enable a good fit in closing the VSD. The right coronary artery button was removed with a small cuff from the sinus of Valsalva, while the left coronary artery takeoff was left intact to enable aortic root rotation. The defect of the right coronary ostium that was left after harvesting was closed primarily by suture. The LVOT was opened, and the subpulmonic stenotic lesion was resected. The mobilized aortic root was repositioned to the vicinity of the LVOT by means of a 60° counterclockwise rotation. The VSD was closed with the extension cuff of the right ventricular free wall muscle. Next, we performed the LeCompte maneuver, before reattaching the ascending aorta with a rotation and reimplanting the right coronary button. Reconstruction of the right ventricular outflow tract (RVOT) included direct anastomosis of the posterior wall of the pulmonary trunk to the anterior surface of the harvested right ventricular free wall extension. An autologous fresh pericardial patch was used to complete the anterior half of the RVOT.

The patient's postoperative hemodynamic recovery was excellent, and he was doing well 30 months after the operation.

Key words: *Abnormalities, multiple/surgery; aorta/surgery; cardiac surgical procedures; heart ventricles/surgery; transposition of great vessels/surgery*

From: *Division of Cardiovascular Surgery, Keio University, Tokyo 160-8582, Japan*

Address for reprints:
Ryo Aeba, MD, Division of Cardiovascular Surgery, Keio University, 35 Shinanomachi, Shinjuku, Tokyo 160-8582, Japan

E-mail:
aeba@sc.itc.keio.ac.jp

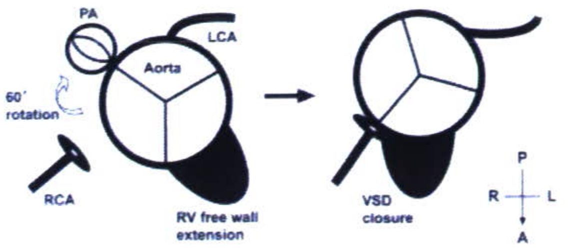

Fig. 1 *A cross-sectional drawing shows aortic translocation with use of autologous tissue.*

A = anterior; L = left; LCA = left coronary artery; P = posterior; PA = pulmonary artery; R = right; RCA = right coronary artery; RV = right ventricle; VSD = ventricular septal defect

Discussion

In 1984, Nikaidoh[2] reported an innovative surgical technique in which the entire aortic root is translocated to the posterior of the heart for treating the complex congenital cardiac anomaly present in patients such as ours. Aortic translocation has a potential benefit over more conventional repairs. In a conventional repair, the aortic root is left in the original position, and the rerouted outflow of each ventricle inevitably must make a sharp-angled turn, which may contribute to the suboptimal late outcome that has been reported with this approach.[3] To date, the use of aortic translocation has not been

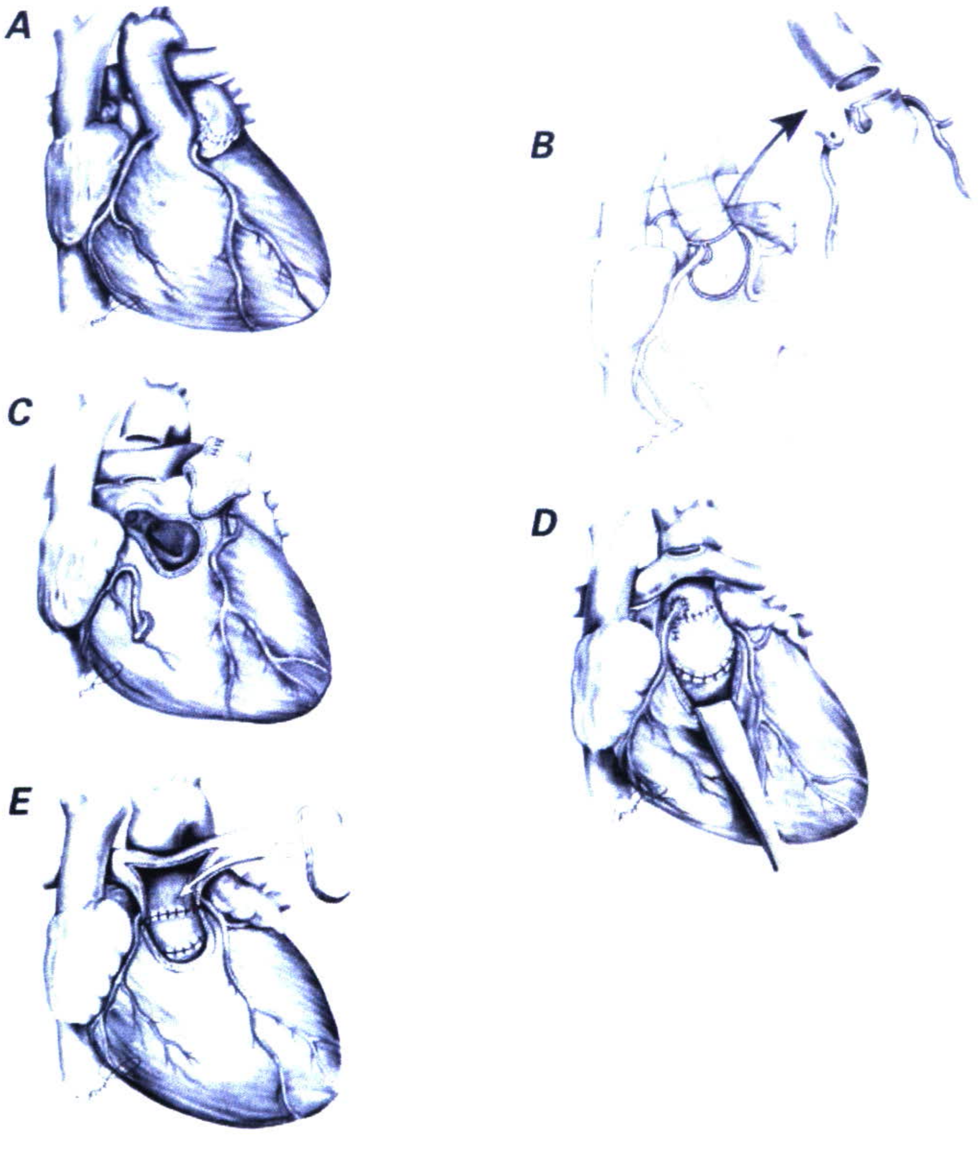

Fig. 2 *Schematic representation of the surgical technique of aortic translocation with use of autologous tissue.* ***A)*** *Appearance of the gross anatomy, with transposition of the great vessels {S,D,L}.* ***B)*** *The planned incision sites at the aorta, pulmonary trunk, right coronary takeoff, and right ventricular outflow tract.* ***C)*** *The mobilized aortic root and detached right coronary artery.* ***D)*** *Aortic translocation with ventricular septal defect closure by means of the right ventricular free wall muscle extension.* ***E)*** *Reconstruction of the right ventricular outflow tract without the use of a prosthesis.*

widespread, partly because of the highly demanding nature of the procedure and the associated risk of coronary kinking and aortic valve regurgitation. However, several surgeons have recently introduced innovations in the performance of aortic translocation.[4] For example, the ascending aorta may be once divided and re-anastomosed with some rotation, with or without the LeCompte maneuver. One or both of the coronary arteries may be detached from the aortic root and then reimplanted in the appropriate new position if coronary kinking is likely to develop. These surgical procedures are quite analogous to the arterial switch operation.

In our patient, we further modified the technique by using autologous tissue from the harvested aortic root together with an extension of the right ventricular free wall. This manner of harvesting is similar to that used in the Ross-Konno procedure.[5] We determined the optimal location of the most proximal edge of the right ventricular free wall extension by use of a right-angle forceps placed through the ascending aorta and the aortic valve to ensure that the extension would close the VSD, which was previously inspected through a right atriotomy.

Our modification—autologous tissue reconstruction of the LVOT—has several advantages. First, this technique saves 1 suture line between the anterior aortic annulus and the prosthetic patch, therefore simplifying aortic translocation and eliminating a potential site of surgical bleeding and a residual defect. Second, with this technique, the aortic root is free of any suture load when the RVOT is reconstructed, because it has been lowered below the level of the aortic annulus and because the configuration of the aortic sinus of Valsalva is better preserved. Third, when our modification is used, the anterior aortic wall is not tethered, in contrast with aortic translocation performed with VSD patch closure, which tethers the anterior aortic wall and may cause late aortic regurgitation. Lack of a prosthetic patch in the LVOT, which includes the aortic annulus, subjects the aortic annulus to less shear stress and enables the LVOT to grow more uniformly, which might improve the long-term result. Our patient's cardiac anatomy is not uncommon in patients with this anomaly. Therefore, an autologous tissue repair could be used in most cases; patients in whom it would not be appropriate include those with an abnormal coronary artery crossing the right ventricular free wall, a small right ventricular volume, or multiple muscular VSDs.

This report shows that aortic translocation with biventricular outflow reconstruction by means of autologous tissue is technically feasible. Possible advantages over the classic Rastelli, LeCompte, and Nikaidoh procedures need to be demonstrated over time, through the accumulation of surgical experience and long-term follow-up.

References

1. Gittenberger-de Groot AC, Sauer U, Oppenheimer-Dekker A, Quagebeur JM. Coronary arterial anatomy in transposition of the great arteries: a morphologic study. Pediatr Cardiol 1983;4(Suppl 1):15-24.
2. Nikaidoh H. Aortic translocation and biventricular outflow tract reconstruction. A new surgical repair for transposition of the great arteries associated with ventricular septal defect and pulmonary stenosis. J Thorac Cardiovasc Surg 1984;88:365-72.
3. Kreutzer C, De Vive J, Oppido G, Kreutzer J, Gauvreau K, Freed M, et al. Twenty-five-year experience with Rastelli repair for transposition of the great arteries. J Thorac Cardiovasc Surg 2000;120:211-23.
4. Morell VO, Jacobs JP, Quintessenza JA. Aortic translocation in the management of transposition of the great arteries with ventricular septal defect and pulmonary stenosis: results and follow-up. Ann Thorac Surg 2005;79:2089-93.
5. Reddy VM, Rajasinghe HA, Teitel DF, Haas GS, Hanley FL. Aortoventriculoplasty with the pulmonary autograft: the "Ross-Konno" procedure. J Thorac Cardiovasc Surg 1996;111:158-67.

Gen Thorac Cardiovasc Surg (2008) 56:36–38
DOI 10.1007/s11748-007-0187-6

CASE REPORT

A case report of surgical correction for congenital mitral regurgitation with subvalvular apparatus abnormality

Mikihiko Kudo, MD · Ryohei Yozu, MD
Ryo Aeba, MD · Kiyokazu Kokaji, MD
Naritaka Kimura, MD · Shiro Iwanaga, MD

Received: 28 August, 2007 / Accepted: 4 October, 2007

Abstract We report a successful complex mitral valve plasty using port access minimally invasive cardiac surgery for congenital mitral regurgitation that presented as an abnormality of the subvalvular apparatus. A 16-year-old male patient received a diagnosis of mitral regurgitation resulting from tethering of the anterior mitral leaflet and posterior mitral leaflet caused by an abnormality in papillary muscle insertion and a hypoplastic chordae tendineae. The posterior leaflet was closely tethered to the tips of the papillary muscle with essentially no chordae tendineae. The flexibility of the leaflet was restored by surgically removing the abnormal chordae, and reconstruction of chordae tendinae of the anterior leaflet was carried out using three loops and of the posterior leaflet using one loop with a loop technique method. As an additional procedure for persistent regurgitation, an edge-to-edge technique to the posterior commissure side was performed, after which the mitral regurgitation disappeared.

Key words Loop technique · Mitral valve plasty · Subvalvular apparatus abnormality · Port access minimally invasive cardiac surgery · MICS

Introduction

Various surgical techniques have been reported for mitral valve plasty (MVP), all of which show good results.[1,2] MVP is enabled by adjusting various techniques in the case of a complicated lesion. We report a successful complex MVP using port access minimally invasive cardiac surgery (MICS)[3] for congenital mitral regurgitation that presented as an abnormality of the subvalvular apparatus.

Case report

A 16-year-old male patient who had been followed for 4 years at another hospital under a diagnosis of mitral regurgitation (MR) was referred to our hospital for a detailed examination because he became aware of breathlessness during exercise. On admission, his height was 159 cm, body weight was 57 kg, and blood pressure was 116/70 mmHg. On physical examination, a high-pitched systolic regurgitant murmur (Levine III/VI) at the lower left sternal border and a low-pitched early-diastolic rumble at the apex were detected. Electrocardiography showed left ventricular hypertrophy with normal sinus rhythm. Echocardiography revealed moderate MR resulting from tethering of the anterior mitral leaflet (AML) and posterior mitral leaflet (PML) caused by an abnormality in papillary muscle insertion and a shortening of the chordae tendineae. Notably, the PML was closely tethered to the tips of the papillary muscle with essentially no chordae tendineae (Fig. 1). Progression of MR was accepted in comparison with an echo provided by another hospital. LV end-diastolic and end-systolic dimensions (LVEDD/LVESD) were 58/38 mm, and the

---

M. Kudo (✉) · R. Yozu · R. Aeba · K. Kokaji · N. Kimura
Department of Surgery, School of Medicine, Keio University, 35 Shinano-machi, Shinjuku-ku, Tokyo 160-8582, Japan
Tel. +81-3-3353-1216; Fax +81-3-5379-3034
e-mail: m-kudo@sc.itc.keio.ac.jp

S. Iwanaga
Department of Cardiology, Keio University, Tokyo, Japan

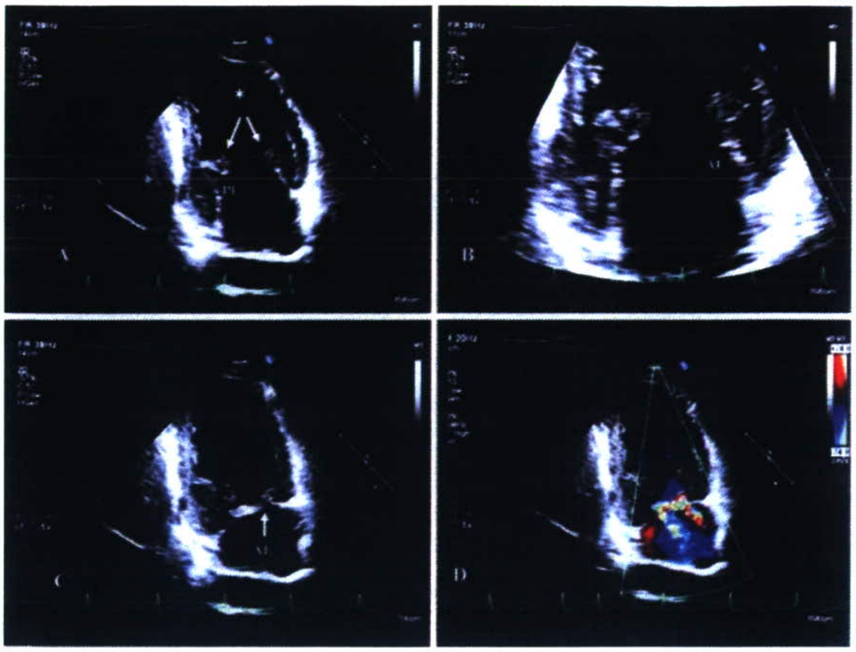

Fig. 1 Preoperative echocardiography. **A,B** Abnormality in papillary muscle insertion (*). The posterior leaflet was severely tethered to the tips of the papillary muscle with essentially no chordae tendineae. **C** A central part of the anterior leaflet was tethered by secondary chorda tendineae (*arrows*). **D** Doppler color flow image shows the regurgitation jet from the two junctions of the mitral valve. **A,B** Diastolic phase; **C,D** systolic phase. *PL*, posterior mitral leaflet; *AL*, anterior mitral leaflet

LV ejection fraction was 59%. The posteromedial papillary muscle insertion site and inferoposterior LV wall showed severe hypokinesis. Under cardiac catheterization, a pressure study showed that LV end-diastolic pressure was 13 mmHg and pulmonary artery wedge pressure was 12 mmHg. Furthermore, LVEDV showed 178.7 ml, showing potential for the enlargement of left ventricle volume.

Operative technique

Cardiac exposure was obtained by right anterior small thoracotomy by means of port access MICS. The mitral valve and subvalvular apparatus were observed via right-sided left atriotomy. The flexibility of the AML was maintained and the leaflet was approximately normal; however, two secondary chorda tendinaes were fixed to a portion of the central part of the AML. The PML presented a fixation such that it was drawn into the free wall of the left ventricle. The secondary chorda tendinae of the AML was removed, and the flexibility of the PML was restored by surgically removing the three short chordae tendinae that had been attached to it. Next, replacement of these chordae tendineae was performed using the loop technique (5-0 Gore-Tex polytetrafluoroethylene sutures).[4] After having fixed the neochordae with two loops to each papillary muscle, reconstruction of the AML was carried out using three loops and of the PML using one loop (Fig. 2). A coaptation line and movement of the bileaflet valve proved satisfactory in this plasty; however, a small degree of MR remained on the posterior commissure side. As an additional procedure for persistent MR, an edge-to-edge technique to the posterior commissure side was performed, after which the MR disappeared. Ring annuloplasty was carried out using a 32-mm Cosgrove annuloplasty ring. After this procedure, transesophageal echocardiography revealed a dramatic reduction of MR; however, extremely mild mitral stenosis remained (Fig. 3). The postoperative course was uneventful.

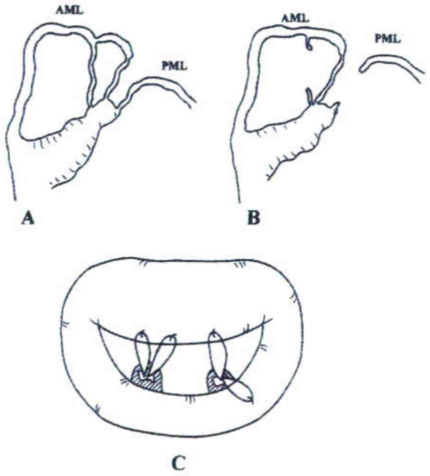

Fig. 2 Schematic presentation of the surgical procedure. Secondary chordae of the anterior leaflet and abnormal shortening of chordae of the posterior leaflet were divided to allow the flexibility of the leaflet (**A,B**). Reconstruction using a loop technique of the AML was carried out using three loops and of the PML using one loop. *AML*, anterior mitral leaflet; *PML*, posterior mitral leaflet

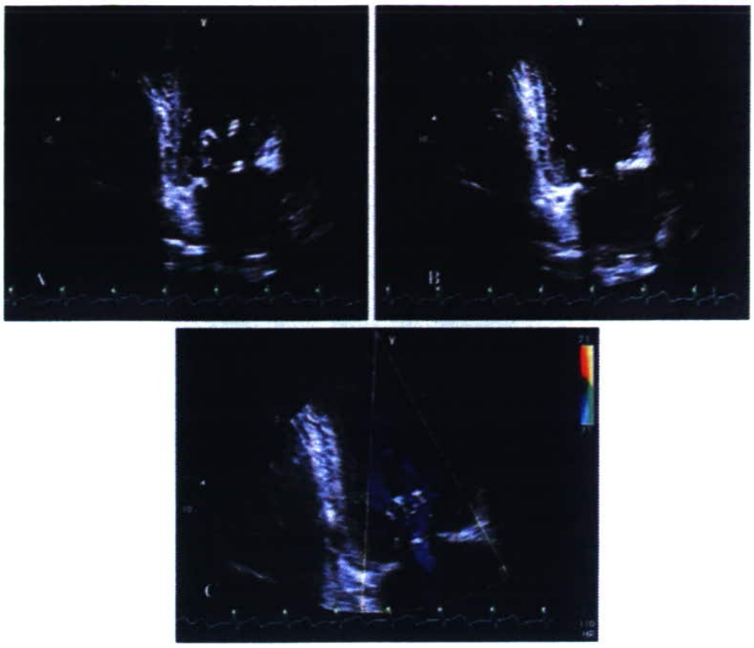

Fig. 3 Postoperative echocardiography showed physiological movement of both leaflets and no residual mitral regurgitation

Discussion

In this case, because the MR had resulted from abnormal papillary muscle insertion and marked foreshortening of the chordae tendineae, use of the standard MVP procedure was difficult. For valvuloplasty in younger patients, the ideal approach is to perform valve plasty while securing as wide a mitral valvular area as possible to allow for future physical growth. A valvular excision and resuture can cause partial degradation of leaflet mobility as a result of consolidation and cicatrization.[5] In this patient, therefore, the loop technique was employed in an attempt to preserve the mobility of the posterior mitral leaflet, to allow a broad range of plasty and to maintain as large a mitral valve area as possible.[6] The aberrant short chordae causing tethering were therefore surgically removed to permit recovery of the flexible leaflet. Because multiple neochordae tendineae were necessary in this case, artificial chorda replacement was employed using the loop technique. Using this method, a satisfactory coaptation line was successfully formed by reconstruction with neochordae, and a loop technique method that permitted multiple and simultaneous replacement proved effective.[4] A second congenital anomaly resulted in a papillary muscle being present in the vicinity of a mitral valve. It appeared likely that physiological movement of the leaflet would be inhibited by this papillary muscle because it was in close proximity to the leaflet edge. As a solution, the distance between the papillary muscle and the valve leaflet was increased by fixing the neochorda unit to the central portion of the papillary muscle. Preservation of physiological leaflet motion was thus enabled.

Valve replacement can now be performed safely with relatively low morbidity and mortality. However, the MVP is preferable in young patients because it reduces the need for long-term anticoagulation treatment and provides a more physiological correction of the lesion. MVP in MR caused by congenital anomaly appears to be feasible by adopting various techniques, as was demonstrated in this case. In addition, initial operations using port access MICS will enable safe reoperation using standard procedures in the future.

References

1. David TE, Ivanov J, Amstrongs S, Christie D, Rakowski H. A conparison of outcomes of mitral valve repair for degenerative disease with posterior, anterior and bileaflet prolapse. J Thorac Cardiovasc Surg 2005;130(5):1242–9.
2. David TE, Armstrong S, Sun Z. Replacement of chordae tendineae with Gore-Tex suture: a ten-year experience. J Heart Valve Dis 1996;5:352–5.
3. Yozu R, Shin H, Maehara T. Minimally invasive cardiac surgery by the port-access method. Artif Organs 2002;26:430–7.
4. Oppell UOV, Mohr FW. Chordal replacement for both minimally invasive and conventional mitral valve surgery using premeasured Gore-Tex loops. Ann Thorac Surg 2000;70:2166–8.
5. Kudo M, Yozu R, Kokaji K, Iwanaga S. Feasibility of mitral valve repair using the loop technique. Ann Thorac Cardiovasc Surg 2007;13:21–6.
6. Kudo M, Yozu R, Kokaji K, Anzai T, Iwanaga S. Mitral valve plasty using "loop technique" method. Heart 2006;38(5):459–65.