SURGERY FOR ACQUIRED HEART DISEASE

MINIMALLY INVASIVE CARDIOPULMONARY BYPASS WITH CARDIOPLEGIC ARREST: A CLOSED CHEST TECHNIQUE WITH EQUIVALENT MYOCARDIAL PROTECTION

Daniel S. Schwartz, MD^a
Greg H. Ribakove, MD^a
Eugene A. Grossi, MD^a
John H. Stevens, MD^b
Lawrence C. Siegel, MD^c
Frederick G. St. Goar, MD^d
William S. Peters, MB, ChB^b
David McLoughlin, MD^a
F. Gregory Baumann, PhD^a
Stephen B. Colvin, MD^a
Aubrey C. Galloway, MD^a

Thoroscopic cardiac surgery is presently under intense investigation. This study examined the feasibility and efficacy of closed chest cardiopulmonary bypass and cardioplegic arrest in comparison with standard open chest methods in a dog model. The minimally invasive closed chest group ($n = 6$) underwent percutaneous cardiopulmonary bypass and cardiac venting, as well as antegrade cardioplegic arrest through use of a specially designed percutaneous endovascular aortic occluder and cardioplegic solution delivery system. The control group ($n = 6$) underwent standard sternotomy and conventional open chest cardiopulmonary bypass, aortic crossclamping, and antegrade cardioplegia. Ischemic arrest time was 1 hour in each group. Ventricular pressures and sonomicrometer segment lengths were recorded before bypass and at 30 and 60 minutes after bypass. Left ventricular function did not differ significantly between the two groups, as demonstrated by measurements of elastance and end-diastolic stroke work. Also, the preload recruitable work area was 69% and 60% of baseline at 30 and 60 minutes after bypass in the minimally invasive group versus 65% and 62% in the conventional control group ($p =$ not significant); the stroke work end-diastolic length relationship was 78% and 71% of baseline in the minimally invasive group at these intervals versus 77% and 74% in the conventional control group ($p =$ not significant). Myocardial temperatures were similar throughout bypass in the two groups, and ultrastructural examination of prebypass and postbypass biopsy specimens showed no differences between groups. These results demonstrate that minimally invasive cardiopulmonary bypass with cardioplegic arrest is as feasible, safe, and effective as conventional open chest cardiopulmonary bypass. Thus current technology may allow wider clinical application of closed chest cardiac surgery. (J THORAC CARDIOVASC SURG 1996;111:556-66)

Recent enthusiasm for minimally invasive surgery has been fueled by the success of laparoscopic and thoroscopic techniques. These methods have

allowed patients to undergo increasingly complex procedures without the pain and morbidity associated with standard open surgical techniques. The benefits of such an approach are obvious. Until recently, however, minimally invasive cardiac surgery has not been feasible, mainly because of limitations in percutaneous perfusion technology, limitations in operative exposure and suturing techniques with the closed chest approach, and lack of availability of a percutaneous myocardial protection system.

As early as 1962 Dennis and associates¹ described the use of left heart bypass without thoracotomy for surgical catastrophes that could not be addressed by other means. Others subsequently reported successful application of percutaneous cardiopulmonary support systems.²⁻⁷ These previous methods, how-

From the Department of Surgery, Division of Cardiothoracic Surgery,^a New York University Medical Center, New York, N.Y., and the Departments of Cardiothoracic Surgery,^b Anesthesia,^c and Medicine,^d Stanford University School of Medicine, Palo Alto, Calif.

Funded in part by a grant from Heartport, Inc., Redwood City, Calif.

Received for publication June 23, 1995; accepted for publication Oct. 3, 1995.

Address for reprints: Greg H. Ribakove, MD, 530 First Ave., Suite 6D, New York University Medical Center, New York, NY 10016.

Copyright © 1996 by Mosby-Year Book, Inc.

0022-5223/96 \$5.00 + 0 12/1/69655

ever, were developed primarily for use in emergency situations and for temporary cardiac support. Likewise, femoral vein–femoral artery cardiopulmonary bypass (CPB) has been in use for decades, and improved percutaneous perfusion systems recently have become available. Nevertheless, until now these systems have had limited appeal as a result of certain inherent disadvantages. For example, no minimally invasive system has yet been able to simultaneously provide effective CPB and cardioplegic arrest. In addition, ventricular decompression and venting have not been possible during percutaneous perfusion. Moreover, the feasibility of percutaneous cardioplegic arrest and myocardial protection has not been well established. If minimally invasive closed chest cardiac surgery is to develop, these issues need to be resolved.

The original percutaneous myocardial protection system was proposed and developed at Stanford University. Our laboratories recently have undertaken a series of studies to examine in an animal model the feasibility of closed chest cardiac surgical techniques. These include newly developed endovascular myocardial protection systems and thoracoscopic dissection and suture methods, applied in conjunction with conventional techniques, such as diathermy-assisted dissection and percutaneous femoral vein–femoral artery bypass. The two purposes of this study were (1) to determine if percutaneous minimally invasive CPB and cardioplegic arrest are feasible with newly available technology and (2) to compare the effectiveness of the minimally invasive approach with that of conventional methods.

Materials and methods

Study groups. Twelve heartworm-free mongrel dogs (25 to 30 kg) were divided into two groups. In the minimally invasive group ($n = 6$) CPB was established with an endovascular aortic clamp (Endoclamp device; Heartport, Inc., Redwood City, Calif.) used for aortic occlusion and endovascular delivery of cardioplegic solution and an endovascular pulmonary artery venting catheter (Heartport) for pulmonary artery venting. In the conventional group ($n = 6$) CPB was established by opening the chest and using a standard aortic crossclamp with antegrade delivery of cardioplegic solution into the aortic root via an aortic root catheter and a standard pulmonary artery vent. All animals were given humane care in compliance with the “Principles of Laboratory Animal Care” formulated by the National Society for Medical Research and the “Guide for the Care and Use of Laboratory Animals” prepared by the Institute of Laboratory Animal Resources and published by the National

Institutes of Health (NIH Publication No. 86-23, revised 1985).

Surgical preparation. In all animals anesthesia was initiated with a 4% solution of thiamylal (0.5 mg/kg) and maintained with metocurine iodide (0.5 mg/kg) and α -chloralose (100 mg/kg) after endotracheal intubation. The animals were supported with a mechanical ventilator (Harvard Apparatus Co., Dover, Mass.) and their lungs were ventilated with 100% oxygen. All animals were monitored throughout the entire procedure with electrocardiography and measurement of carotid arterial pressure with a micromanometer (Koenigsberg Instruments Inc., Pasadena, Calif.), pulmonary artery and central venous pressures with a pulmonary artery catheter (Arrow International, Inc., Reading, Pa.), and oxygen saturation via an external pulse oximeter. Arterial blood gases and pH were kept in the normal range by adjusting inspired oxygen concentration and minute ventilation or by administering sodium bicarbonate. Electrolyte and hematocrit levels were also monitored at appropriate intervals throughout the procedure. No transfusions were given to either group.

Surgical technique

Minimally invasive CPB group. The technique of minimally invasive CPB was accomplished as shown in Fig. 1. A femoral venous catheter (17F cannula, model 58517, DLP, Inc., Grand Rapids, Mich.) was placed through a cutdown in the left femoral vein and guided by means of a fluoroscope (MCA 30, Ratheon, Tokyo, Japan) over a guide wire to a position just within the superior vena cava. A femoral arterial cannula (14F, model 57414, DLP) was placed into the left femoral artery. These catheters were connected to the bypass pump (Shiley S-100A Bubble Oxygenator, Shiley Inc., Irvine, Calif., and Pemco roller pump, model 5745, Pemco Inc., Cleveland, Ohio) in a standard fashion. Next, an endovascular pulmonary artery venting catheter (Heartport) was inserted into the external jugular vein and guided into position over a flow-directed pulmonary artery balloon catheter by means of fluoroscopy. The pulmonary artery venting catheter served the dual purpose of monitoring pulmonary artery pressure while in line with a pressure manometer or decompressing the left ventricle during CPB.

An endovascular aortic clamp (Endoclamp device) was positioned under fluoroscopic guidance via the femoral artery into the ascending aorta by means of a guide wire and dilator. The Endoclamp device is a triple-lumen catheter with an inflatable balloon at its distal end. Positioning of the balloon was initially confirmed with instillation of a small aliquot of dilute radiopaque contrast medium (Hypaque sodium; Sanofi Winthrop Pharmaceuticals, New York, N.Y.) through the central lumen, which communicates with the tip of the catheter positioned in the aortic root. The balloon, inflated via the second lumen, provided an endovascular “crossclamp” by occluding the ascending aortic outflow tract (Fig. 2). The balloon was positioned so that it rested in the aorta without occlusion of the coronary ostia or aortic arch vessels. Proper placement of the balloon was confirmed by the instillation of approximately 10 ml of 50% radiopaque contrast material through the central lumen into the aortic root while the balloon was inflated. The position of the

Fig. 1. Diagram of the minimally invasive CPB system used in this series of experiments.

Endoclamp device was also reevaluated before deflation of the balloon at the end of crossclamping. Cardioplegic solution was delivered through the central lumen, which also acted as an aortic root vent. Aortic root pressure was monitored through a third separate lumen. The chest remained closed throughout the placement of these catheters. A small subxiphoid incision was made for placement of crystals to measure segment length and temperature probes, as discussed later in this article. Bicaval control was obtained with the use of an umbilical tape and snare. The subxiphoid incision was reapproximated after placement of all monitoring devices and before any measurements of cardiac function, pressure, or temperature were made.

Conventional CPB group. In the conventional group a standard approach was used to implement CPB. The chest cavity was surgically opened in the midline with a median

sternotomy and remained open throughout the entire experiment. CPB was achieved after a venous catheter (32F, model V 122-32, Stöckert-Shiley, Irvine, Calif.) was inserted into the right atrial appendage and secured in position. An arterial cannula (16F, USCI, C.R. Bard, Inc., Billerica, Mass.) was placed into the left femoral artery, and a 16-gauge Angiocath catheter (Deseret Medical, Sandy, Utah) was used to vent the pulmonary artery. A separate 18-gauge Angiocath catheter was inserted into the ascending aorta and used to deliver cardioplegic solution, to vent the aortic root, or to measure aortic root pressures. Bicaval control was obtained in the manner previously described.

CPB and delivery of cardioplegic solution. All animals underwent total CPB after systemic delivery of heparin (100 U/kg). They were cooled to a temperature of 28° C and subjected to CPB at flow rates of approximately 100

Fig. 2. Roentengram illustrating the proper position of the endovascular aortic clamp (*EAC*) in the ascending aorta with opacification of the balloon at the tip of the catheter. The endovascular pulmonary artery venting catheter (*EPV*) and the venous bypass cannula (*VC*) are overlying the cardiac silhouette.

ml/kg per minute. Arterial oxygen tension was maintained at greater than 70 mm Hg, and the mean arterial pressure during CPB was maintained at greater than 60 mm Hg by adjusting CPB flow. Venous return was aided in both groups by attachment of the venous return cannula to a centrifugal pump (Bio-pump, Medtronic Bio-Medicus, Eden Prairie, Minn.). The ascending aorta was occluded with a vascular clamp or by inflation of the balloon of the Endoclamp device. Multiple doses of cardioplegic solution were given antegradely either through the distal end of the Endoclamp device or through the aortic root catheter. Both groups received Freme's cardioplegic solution,⁸ and oxygenated blood cardioplegic solution was cooled to 6° C in a BCD Plus Heat Exchanger (Shiley). A high potassium dose of 20 ml/kg (20 to 24 mEq/L final concentration) was given initially to arrest the heart, followed by a potassium mixture of 10 ml/kg (8 to 12 mEq/L final concentration) given at 15-minute intervals. All doses were given at a rate of 75 ml/min with blood mixed with cardioplegic solution in a ratio of four to one. The hematocrit value during CPB remained above 25% in all cases. The pulmonary artery and the aortic root were vented throughout CPB and drained into the oxygenator reservoir. After 1 hour of CPB, the blood temperature was warmed to more than 35° C and the aorta was unclamped. If necessary, the heart was defibrillated. The heart was then allowed to rewarm to 37° C. Data acquisition was continued for 60 minutes after the completion of CPB.

Measurement of left ventricular segment length and pressure. Instantaneous myocardial segment dimensions were measured with subepicardial pulse-transit ultrasonic dimension transducers (model CY5; Triton Technology, Inc., San Diego, Calif.). They were placed in the epicardium, via a stab incision, 5 cm apart along the left

ventricle, midway between the base and apex. The piezoelectric crystals were then connected to an oscilloscope and sonomicrometer (model 100; Triton Technology) for calibration and recording of analog output.

Ventricular pressures were recorded continuously with micromanometers (models MPC-500 and SPC-450; Millar Instruments, Inc., Houston, Tex.) placed into the apices via stab incisions. All micromanometers were calibrated over a similar range and then allowed to equilibrate to 37° C. The sinus node was crushed with a clamp, and the right atrium was electronically paced (Medtronic, Inc., Minneapolis, Minn.) at a constant rate of 150 beats/min.

Myocardial contractile data acquisition and analysis. Ventricular pressure and myocardial segment dimensions were measured just before CPB (pre-CPB), 30 minutes after the completion of CPB, and 60 minutes after the completion of CPB. Five sets of data were acquired during each measurement. Each set of data acquisition lasted 30 seconds and was recorded over a range of left ventricular end-diastolic volumes produced by transient (10 seconds) bicaval occlusions. The method for measuring cardiac function was based on algorithms developed by other investigators.⁹⁻¹³ The indexes of regional left ventricular systolic contractile function calculated were the slope of the end-diastolic pressure-length relationship (M_w), the x-intercept of the end-diastolic pressure-length relationship (L_w), the preload recruitable work area, the stroke work-end-diastolic length relationship, and maximal regional elastance (E_{max}).

Ventricular temperature measurements. Myocardial thermistors were placed into the right and left ventricular free walls and attached to a digital thermometer (Shiley). Temperature readings were made just before CPB, at 5-minute intervals throughout CPB, and after the comple-

Fig. 3. A, Representative plot of instantaneous left ventricular pressure and myocardial segment length dimension for cardiac cycles over a range of end-diastolic volumes. B, Left ventricular regional stroke work expressed as a function of end-diastolic length for each cardiac cycle yields linear relationship with a slope and x-intercept. C, The area under the segmental preload recruitable work area versus end-diastolic length relationship is equal to the preload recruitable work area (equation 3) for two different time periods in the same subject. L_{w1} and L_{w2} are the different x-intercepts and L_{wmax} is the maximal value of the x-intercept for the entire experiment.

tion of CPB. Blood temperature and cardioplegic solution temperature were also measured in series with the CPB circuit (YSI series 500; Yellow Springs Instrument Company, Yellow Springs, Ohio).

Ultrastructural and histologic examination. Ultrastructural examination was performed on transmural needle biopsy specimens taken from the apex of each ventricle before CPB and at 30 and 60 minutes after completion of CPB. Most specimens were embedded in paraffin, stained with hematoxylin and eosin, and examined with a high-power light microscope. Representative specimens were also prepared for examination by transmission electron microscopy by being rapidly immersed in fresh, cold 3% glutaraldehyde in Sorensen's phosphate buffer (0.1 mol/L, pH 7.3) for 24 hours. The specimens were then fixed in 1% osmium tetroxide, dehydrated in acetone, and embedded in Epon fixative. "Green" sections 0.5 to 1 μ m thick were cut, stained with a polychrome stain, and examined by light microscopy for orientation purposes. Corresponding thin sections were cut with an LKB Ultratome III knife (LKB Instruments, Inc., Rockville, Md.), mounted on copper-coated grids, stained with uranyl acetate and lead acetate, and then examined with a Siemens transmission electron microscope (Siemens Medical Corp., Iselin, N.Y.). Specimens were qualitatively evaluated for myocyte necrosis, intercellular or intracellular edema, mitochondrial and myofilament abnormalities, cell membrane disruption, and microvascular damage.

Statistical methods. Data were analyzed by the SPSS for Windows statistical software program (SPSS, Inc., Chicago, Ill.). All results are expressed as the mean $\pm$ standard deviation. The statistical significance of changes in load-independent indexes of ventricular function were

compared by repeated-measures analysis of variance. Significance was determined at the level of 5% or less.

Results

Regional myocardial contractile function. When the instantaneous left ventricular intracavitary pressure was plotted against the regional left ventricular segment length, pressure-length work loops resulted (Fig. 3). At baseline before the institution of CPB, regional myocardial function did not differ in the minimally invasive versus conventional groups. There were no significant differences in the slopes (143.2 ± 12.9 vs 131.3 ± 21.9 erg $\times$ cm⁻¹ $\times 10^3) or the x-intercepts (4.8 ± 1.0 vs 4.3 ± 0.7 cm) ($p = \text{NS}$) (Table I). The mean linear correlation coefficient for the end-diastolic pressure-segment length relationship before and after CPB was 96%. There were no significant changes with respect to between-subject effects in the x-intercept at both 30 and 60 minutes after the completion of CPB (Fig. 4). There were also no significant changes in the slope after the completion of CPB (Fig. 5). The mean percentage standard deviations were 3% and 5% for the variables slope and x-intercept, respectively. Power analysis of our experimental protocol revealed that with a power of 80% and a two-tailed t test at the level of 5%, we were able to detect a difference$

Fig. 4. X-axis intercept (L_w) of the end-diastolic pressure-length relationship represented as *boxplots* of the mean values before and after CPB. NS, Not significant.

Table I. Effects of minimally invasive and conventional CPB and cardioplegic arrest on myocardial contractile function

	Before CPB	30 min after CPB	60 min after CPB	Significance*
M_w (erg · cm ⁻³ · 10 ³)				
Minimally invasive	143.2 ± 12.9	127.5 ± 17.8	122.3 ± 17.6	$p = NS$
Conventional	131.3 ± 21.9	122.5 ± 23.0	119.1 ± 22.0	
L_w (cm)				
Minimally invasive	4.8 ± 1.0	5.2 ± 1.0	5.4 ± 1.1	$p = NS$
Conventional	4.3 ± 0.7	5.0 ± 0.6	5.0 ± 0.6	
E_{max} (mm Hg/cm)				
Minimally invasive	125.4 ± 58.7	143.0 ± 69.7	132.0 ± 84.9	$p = NS$
Conventional	107.3 ± 50.9	103.8 ± 59.8	101.4 ± 60.2	
PRWA (%)				
Minimally invasive	100	69 ± 16	60 ± 11	$p = NS$
Conventional	100	65 ± 18	62 ± 18	
SWEDL (%)				
Minimally invasive	100	89 ± 11	85 ± 10	$p = NS$
Conventional	100	93 ± 05	91 ± 04	

Values are mean ± standard deviation. Slope (M_w), x-intercept (L_w), preload recruitable work area (PRWA), stroke work–end-diastolic length relationship (SWEDL), and maximal regional elastance (E_{max}). Preload recruitable work area and stroke work–end-diastolic length relationship are expressed as a percent of the prebypass values.

*Differences between groups tested by two-way analysis of variance for repeated measures.

between treatment groups if the percentage difference between the groups was more than 5% for x-intercept and more than 8% for slope.¹⁴

No significant differences between groups were observed in the preload recruitable work area (Table I, Fig. 6) or stroke work–end-diastolic length relationships (Fig. 7) at 30 and 60 minutes. The mean linear correlation coefficient for the end-systolic pressure–segment length relationship before and after CPB was 95% in both groups. E_{max} remained relatively constant throughout the experiment (Table I, Fig. 8). The mean changes in E_{max} after CPB at 30 and 60 minutes were not statistically significant.

Ventricular venting and delivery of cardioplegic solution. All subjects' hearts arrested within 90 seconds after the institution of cardioplegia. Ventricular venting was obtained in all experiments and verified by monitoring of left and right ventricular pressure throughout CPB. The pressures remained at 0 to 10 mm Hg after pulmonary artery and aortic root venting were instituted and remained at that level throughout the CPB period.

Myocardial temperature. The right and left ventricular temperatures before, during, and after CPB are depicted in Fig. 9. The mean myocardial pre-CPB temperatures for the minimally invasive and

Fig. 5. Slope (M_w) of the end-diastolic pressure-length relationship represented as a *boxplot* of the mean values before and after CPB. NS, Not significant.

Fig. 6. Myocardial contractile function quantified by work area (PRWA) as a percentage of the mean pre-CPB value. NS, Not significant.

conventional groups were $36.0^\circ \pm 0.8^\circ$ and $36.5^\circ \pm 0.5^\circ$ C, respectively. During CPB the heart was cooled in the minimally invasive and conventional groups to a mean temperature of $17.5^\circ \pm 1.4^\circ$ C and $17.3^\circ \pm 1.0^\circ$ C, respectively. With regard to isolated cooling of the left ventricle in the minimally invasive and conventional groups during CPB, the average temperatures were $17.2^\circ \pm 1.2^\circ$ and $17.5^\circ \pm 1.5^\circ$ C, respectively. The right ventricle was cooled to mean temperatures of $17.3^\circ \pm 1.0^\circ$ C and $17.5^\circ \pm 1.4^\circ$ C, respectively, in the two groups. At the conclusion of aortic crossclamping, the myocardium was rewarmed in the minimally invasive and conventional groups to $31.9^\circ \pm 5.5^\circ$ C and $33.1^\circ \pm 1.3^\circ$ C, respectively (p = not significant). The blood temperatures were all above 35° C in both groups.

Ultrastructural examination. No changes were noted in either group on gross inspection of the postmortem heart specimens. Light microscopic ex-

amination failed to reveal any widespread degenerative changes in the biopsy specimens. Likewise, ultrastructural examination showed no differences between prebypass and postbypass specimens in either group with regard to intracellular or intercellular edema, myofilament and mitochondrial abnormalities, membrane rupture, or microvascular disruption or blockage (Fig. 10).

Discussion

A key point in assessing the efficacy of any new CPB-myocardial protection technique is to determine the technique's potential for minimizing myocardial damage during aortic crossclamping and for promoting the recovery of myocardial performance after reperfusion. In this experiment, all measurements of regional myocardial performance, including the slope and x-intercept of the stroke work versus end-diastolic relationship, the preload re-

Fig. 7. Myocardial contractile function quantified by the stroke work–end-diastolic length relationship (*SWEDL*) as a percentage of the mean pre-CPB value. *NS*, Not significant.

Fig. 8. Emax of the end-systolic pressure–length relationship represented as a *boxplot* of the mean values before and after CPB. *NS*, Not significant.

cruitable work area, the stroke work–end-diastolic length relationship, and the Emax were equivalent in the minimally invasive group and the conventional open myocardial protection group. In addition, the mean percentage standard deviation for each parameter was low with the exception of Emax. Despite the small number of subjects in each group, we were able to compare the treatment groups with respect to the end-diastolic relationships to determine if a difference had occurred.¹⁴ This was possible because of the low percentage standard deviations observed in each group. However, the variability in Emax could have resulted either from magnification of measurement error or, more likely, from the true minute-to-minute variation in cardiac performance.

With the exception of Emax, all of the contractile performance indexes measured are relatively inde-

pendent of preload and afterload and are extremely sensitive to ischemia.¹² Glower and coworkers¹⁰ previously described the variable sensitivity of Emax to ischemia and have attributed it to a reversible phenomenon called diastolic creep. Some of the variability noted in Emax in these experiments may be a creep effect.

A potential limitation of the methods used in the experiment is that measuring dynamic ventricular dimensions rather than volume assumes that regional ventricular hydrodynamic performance accurately reflects global performance. This assumption appears valid because of the consistent correlation between segment length and stroke volume and between regional and global stroke work reported by others.¹³

An important goal of this study was to determine if percutaneous endovascular delivery of cardioplegic solution could cool the myocardium as well as

Fig. 9. Myocardial regional temperatures of the left and right ventricles before, during, and after CPB. NS, Not significant.

standard open antegrade delivery of cardioplegic solution. The results showed equivalent mean temperatures (approximately 17° C) in each group during CPB. This level of hypothermia was achieved despite the absence of topical cooling in these experiments. In addition, the ability to bathe the heart in cool saline solution should be technically feasible in the minimally invasive group. Effective decompression of the heart by the endovascular aortic catheter technique and endovascular pulmonary artery vent proved to be clearly possible. This ability to unload¹⁵ and decompress the heart is thought to be essential for adequate myocardial protection.

The technique of minimally invasive CPB used in this study is based on an innovative percutaneous vascular access device (the Endoclamp device) that provides for endovascular aortic occlusion, delivery of cardioplegic solution, and left ventricular decompression. The Endoclamp device is a triple-lumen catheter with an inflatable balloon at its distal end. Proper positioning of the balloon is paramount because improper placement can result in aortic valve incompetence and left ventricular distention,

unequal distribution of cardioplegic solution, occlusion of the major head vessels, or an inability to adequately arrest the heart. In this study proper positioning of the balloon proved to be easily achievable by means of fluoroscopic guidance, and positioning in human beings should be easier because the ascending aorta is longer in the human being than in the dog, as has been confirmed independently in human cadaver studies. Cardioplegic solution is delivered in an antegrade fashion through a central lumen that communicates with the tip. This lumen also acts to vent the aortic root after delivery of the cardioplegic solution. A second lumen is used to monitor aortic root pressure. The third lumen is used for inflation of the balloon. The pulmonary artery venting catheter is percutaneously placed through the external jugular vein and passed into the pulmonary artery, so that the heart is vented to achieve ventricular decompression.

Use of this system in combination with percutaneous CPB perfusion allowed the hearts in these experiments to be easily arrested, cooled, and vented. The overall results demonstrate that the Endoclamp device in association with the endovas-

Fig. 10. Electron micrographs of left ventricular biopsy specimens from the same animal showing normal ultrastructure before minimally invasive CPB (A) and after 60 minutes of reperfusion (B). (Uranyl acetate and lead citrate, $\times 6600$.)

cular pulmonary artery venting catheter was able to provide complete aortic occlusion, adequate cardioplegic delivery with prompt heart arrest, adequate myocardial cooling, and excellent myocardial functional recovery to an extent equivalent to that of conventional techniques.

The findings of this study demonstrate that minimally invasive CPB and endovascular cardioplegic arrest are technically feasible and effective. The technique provides myocardial protection equivalent to that obtained with open methods. The implications of these findings are significant, because

effective closed chest techniques for myocardial protection are necessary if minimally invasive cardiac surgery is to become a clinical reality. The minimally invasive endovascular myocardial protection system studied here provides the foundation for development of routine methods for accomplishing many types of cardiac operations without median sternotomy or thoracotomy.

We would like to thank Manasse Decady, Francisco Rivera, and Eleones Anglade for their expert technical assistance.

REFERENCES

1. Dennis C, Hall DP, Moreno JR, Senning A. Reduction of the oxygen utilization of the heart by left heart bypass. *Circ Res* 1962;10:298-305.
2. Glassman E, Engelman RM, Boyd AD, Lipson D, Ackerman B, Spencer FC. A method for closed-chest cannulation of the left atrium for left atrial-femoral artery bypass. *J THORAC CARDIOVASC SURG* 1975;69:283-90.
3. Laub GW, Muralidharan S, GU J, et al. Novel system for percutaneous cardiopulmonary bypass. *J Invest Surg* 1991;4:217-30.
4. Rose DM, Colvin SB, Culliford AT, Cunningham JN Jr, et al. Long-term survival with partial left heart bypass following perioperative myocardial infarction and shock. *J THORAC CARDIOVASC SURG* 1982;83:483-92.
5. Rossi F, Kolobow T, Foti G, et al. Long-term cardiopulmonary bypass by peripheral cannulation in a model of total heart failure: the decompression of the left heart through a percutaneous helical spring positioned within the lumen of the tricuspid and pulmonary valves. *J THORAC CARDIOVASC SURG* 1990;100:914-20.
6. O'Neill P, Menedez T, Hust R, et al. Prolonged ventricular fibrillation—salvage using a new percutaneous cardiopulmonary support system. *Am J Cardiol* 1989;64:545.
7. Nishida H, Shibuya M, Kitamura M, et al. Percutaneous cardiopulmonary support as the second generation of venoarterial bypass: current status and future directions. *Artif Organs* 1993;17:903-13.
8. Peters WS. Minimally invasive cardiac surgery by cardioscopy. *Australas J Cardiac Thorac Surg* 1993;2:152-4.
9. Sagawa K, Maughan L, Suga H, Sunagawa K. Chamber pressure-volume relation versus muscle tension-length relation. In: Sagawa K, Maughan L, Suga H, Sunagawa K, eds. *Cardiac contraction and the pressure-volume relationship*. 1st ed. New York: Oxford University Press, 1988:42-109.
10. Glower DD, Schaper J, Kapas JS, et al. Relation between reversal of diastolic creep and recovery of systolic function after ischemic injury in conscious dogs. *Circ Res* 1987;60:850-60.
11. Morris JJ, Pellom GL, Murphy CE, Salter Dr, Goldstein JP, Weschler AS. Quantification of the contractile response to injury: assessment of the work-length relationship in the intact heart. *Circulation* 1987;76:717-27.
12. Glower DD, Spratt JA, Kabas JS, David JW, Rankin JS. Quantification of regional myocardial dysfunction after acute ischemic injury. *Am J Physiol* 1988;255:H85-93.
13. Glower DD, Spratt JA, Tyson GS, et al. Linearity of the Frank-Starling relationship in the intact heart: the concept of preload recruitable work. *Circulation* 1985;71:994-1009.
14. Snedecor GW, Cochran WG. Power of a test of significance. In: Snedecor GW, Cochran WG. *Statistical methods*. 7th ed. Ames, Iowa: The Iowa State University Press, 1980:68-70.
15. Axelrod HI, Galloway AC, Murphy MS, et al. A comparison of methods for limiting myocardial infarct expansion during acute reperfusion—primary role of unloading. *Circulation* 1987;76(Suppl):V28-32.