Mitral valve replacement via a right mini-thoracotomy in the dog: use of carbon dioxide to reduce intracardiac air

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Abstract

Objective: To develop a clinically applicable method of minimally invasive mitral valve replacement (MVR) with cardioplegia, and examine the ability of carbon dioxide (CO2) to improve de-airing. Methods: MVR was performed via a 5 × 3-cm right lateral minithoracotomy in eight greyhounds. Peripheral cardiopulmonary bypass and an ascending aortic balloon catheter (endoaortic clamp) were used for cardioplegia and aortic root venting. The endoaortic clamp was inflated in the ascending aorta under fluoroscopy and cardioplegic solution was infused. In four dogs, CO2 at 2 l/min was used to displace air in the chest. A left atriotomy was made, the valve exposed and a mechanical valve implanted. After left atrial closure, retained intracardiac gas was aspirated from the aortic root and collected in a bubble-trap. The endoclamp was deflated and the animal weaned from bypass.

Results: A satisfactory MVR was performed in all cases. The clamp time was 64 ± 13 min and all dogs were stable post-bypass. In the CO2 group, intrathoracic CO2 was maintained above 86% and 0.1 ± 0.1 ml of gas was collected, compared to 1.3 ± 0.8 ml in the non-CO2 group (P < 0.05). Conclusions: Femoro-femoral bypass and use of the endoaortic clamp allow a safe and efficacious MVR via a right minithoracotomy in the dog. A high intrathoracic CO2 concentration reduces the amount of retained intracardiac gas. © 1997 Elsevier Science B.V.

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1. Introduction

Minimally invasive cardiac surgery on a quiescent heart is made possible by the use of peripheral cannulation for cardiopulmonary bypass and an ascending aortic balloon catheter (endoaortic clamp) for cardioplegia [1,2]. Minimally invasive, or ‘port-access’, MVR via a left lateral minithoracotomy in the dog using a peripheral bypass system has been reported [3]. In humans, the cardiac apex is more lateral than in the dog, and the mitral valve is more readily approached from the right thorax. Minimally invasive mitral valve repair from the right chest using femoral bypass and with the heart fibrillating has been recently described in three patients [4,5]. Without occlusion of the ascending aorta, this approach is hampered by the presence of aortic regurgitation and does not allow controlled de-airing of the heart. Also, femoral venous cannulation can potentially inhibit retraction to expose the valve, and retraction itself may negatively impact on venous drainage of the head and neck if only femoral cannulation is used.

In this study we set out to develop a safe and efficacious technique of port-access MVR via a right mini-thoracotomy, using peripheral bypass and cardio-
plegia. Our major concerns with this approach were firstly the adequacy of superior vena caval drainage using femoral venous cannulation, secondly the exposure and visualization of the mitral apparatus and thirdly the ability to de-air the heart using this restricted approach. This study was also designed to assess the efficacy of a novel helical femoral venous cannula in allowing easy atrial retraction without hindering SVC drainage and the usefulness of a converging lens system for stereoscopic visualization of the valvular apparatus via a minithoracotomy. We also set out to investigate the efficacy of de-airing in the minimally invasive approach to MVR, and to determine whether CO₂ insufflation into the chest would achieve high CO₂ concentrations and reduce retained intracardiac air.

2. Methods

2.1. Study groups

Eight greyhounds (25–33 kg) were used to test the operative technique and assess cardiac de-airing. In six dogs a mitral valve replacement was done, and in two dogs the native mitral valve was exposed but not replaced (sham studies). Of the eight dogs, CO₂ was used to displace air from the chest cavity in four (three replacement, one sham), and no CO₂ was used in the other four. The study was conducted in accordance with the Code of Practice of the National Health & Medical Research Council and approved by the institutional Ethics Committee.

2.2. Surgical method

Anesthesia was induced with Propofol, 0.5 ml/kg IV. The animal was ventilated via an endotracheal tube and anesthesia was maintained with isoflurane and oxygen. A cannula was inserted in the left carotid artery for monitoring systemic arterial pressure. A 7.5-Fr thermodilution catheter was introduced via a sheath in the left external jugular vein to measure central venous (CVP), pulmonary artery (PAP) and pulmonary capillary wedge (PCWP) pressures. Rectal temperature and the electrocardiogram were monitored continuously. Arterial blood gases were measured before, during and after cardiopulmonary bypass.

The cannulations for endovascular cardiopulmonary bypass are shown in Fig. 1. Heparin 300 U/kg was given intravenously (IV). A 8.3-Fr pulmonary vent catheter (Endopulmonary Vent; Heartport Inc., Redwood City, CA) was inserted via the right external jugular vein and floated into the pulmonary artery. A 17-Fr 65 cm femoral venous cannula (Heartport Inc.), with a helical cut made in the distal one third, was passed over an exchange wire in the right femoral vein and the tip positioned in the superior vena cava under fluoroscopic guidance. A centrifugal pump (Centrimed System 1; Sarns, Ann Arbor, MI) was used to augment venous drainage. A 17-Fr arterial cannula (DLP, Grand Rapids MI) was placed in the right femoral artery. A 10.5-Fr balloon catheter (Endoaortic Clamp; Heartport Inc.) was introduced through the left femoral artery and its tip positioned in the ascending aorta under fluoroscopy. Connections were made to the endoaortic clamp for balloon inflation, aortic root pressure monitoring, cardioplegia and venting. A bubble trap was inserted in the aortic root vent line to measure the volume of gas retrieved from the heart after closure of the atriotomy. A pressure relief valve (American Omni Medical, Costa Mesa, CA) was inserted in the vent line between the aortic root bubble trap and the roller pump to avoid cavitation. The venous and arterial lines were connected to the pump oxygenator, CPB was initiated and cooling to 26–28°C begun. The cardioplegia line and the bubble trap were primed to eliminate air.

The dog was rolled 30° to the left. A 5-cm incision was made anterolaterally in the 4th or 5th right intercostal space and a small Finochetto retractor inserted to maintain an opening with minimal rib retraction. The pericardium was incised longitudinally anterior to
the phrenic nerve. Two stay sutures were placed in the parietal pericardium, dorsal to the phrenic nerve, and bought out laterally through the chest wall through 14G needles (Fig. 2). This retracted the right lung and everted the pericardium to expose the intrapericardial right superior pulmonary vein. A 5-mm intercostal port was inserted in the right parasternal line just caudal to the level of the pulmonary root. Port-access forceps inserted through the 5 mm port were used to grasp the right atrial wall. This provided counter-traction to assist dissection of the interatrial groove. In four dogs (CO₂ group) a 1/8 in.-diameter tube was positioned in the base of the right hemi thorax and 100% CO₂ was infused at 2 l/min.

The endoaortic clamp was inflated under fluoroscopy and cold blood cardioplegia (24 mmol/l KCl, 4°C) was infused into the aortic root. Cardioplegia was re-inflused at 15–20 min intervals. A left atriotomy was made and a cardiotomy sucker inserted with suction maintained at 300–500 ml/min. An atrial retractor (Heartport Inc.) was inserted through the parasternal port and used to expose the mitral valve (Fig. 3). Binocular vision through the narrow incision was maintained using a converging lens system and light mounted on a spectacle frame (Lumiveiw 3D; Welch-Allyn, Skaneatales, NY) (Fig. 4).

The valve annulus was sized and interrupted horizontal mattress 2/0 polyester sutures were inserted around the valve annulus, the native leaflets, using thoracoscopic instruments (Port-access Mitral Valve Instrument Set; Heartport Inc). A mechanical Port-Access St Jude mitral valve (St Jude Medical Inc., Minneapolis, MN) was seated in the annulus and the knots secured manually or using a knot-pusher. The sutures were trimmed and leaflet motion tested. In the two sham procedures, to study de-airing alone, the native valve was exposed but no prosthesis was implanted.

The left atriotomy was sutured and left partly open. The pulmonary vent was turned off, venous return restricted and the lungs inflated to fill the cardiac chambers with blood. The heart was agitated to displace gas and the atriotomy closed whilst positive pressure was maintained on the lungs. The aortic root vent was then opened, the lungs inflated and the heart agitated further, and aspirated air was collected in the bubble trap. Normal venous return was then re-established and the endoaortic clamp deflated. If necessary, the heart was defibrillated using internal paddles. Ventilation was resumed, the animal rewarmed above 36°C and bypass discontinued. Aortic root venting via the endoclamp was maintained for 5 min following weaning from bypass. The endoclamp was removed and a 6-Fr pig-tail catheter was passed over a guide wire into the left ventricle for contrast ventriculography and pressure measurements.

2.3. Measurements and statistical analysis

Cardiac output and filling pressure measurements were made just prior to bypass. Cardiac output, PCWP and the left ventricular end-diastolic pressure (LVEDP) were measured 20 min after discontinuation of bypass. The postoperative transvalvular gradient was calculated by subtracting the LVEDP from the simultaneous PCWP.

In the four dogs in which CO₂ was used to displace air, intrathoracic oxygen content was measured using an oxygen analyzer (Therniox Instruments, Pittsburgh, Pennsylvania) calibrated to read atmospheric O₂ at 20.85%. Gas was sampled at the atriotomy. The dilution of O₂ in the gas sample was used to calculate the percent CO₂ in the chest, as follows:

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\text{\% Intrathoracic CO}_2 = 100 - (\text{\% Intrathoracic O}_2 \times 100/20.85)
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Measurements were made of the volume of gas collected in the aortic root gas trap prior to release of the endoaortic clamp and also the total volume of gas trapped in the aortic root trap 15 min following cessation of root venting. No analysis was made of the composition of gases in the bubble trap. Carotid artery bubble traps were found to be insensitive due to low flow, and were abandoned. After euthanasia the heart was excised and a macroscopic examination made.
All data is represented as the mean ± standard deviation. The difference between matched data was calculated using Student’s paired $t$-test or the Mann–Whitney rank sum test where appropriate. A $P$ value of less than 0.05 was used to determine statistical significance.

3. Results

3.1. Mitral valve replacement

A successful MVR was performed in all six cases. An average of 11 mattress sutures were inserted in the...
annulus and a 23 mm valve was implanted in all six dogs without difficulty. At post mortem, all valves were well seated on the annulus and probing did not reveal paravalvular leaks.

The mean CPB time was 111 ± 20 min and the mean aortic clamp time 64 ± 13 min. The CVP and PAP were kept below 5 mmHg during bypass. The endoaortic clamp was effective in occluding the aorta and in enabling antegrade cardioplegic infusion to arrest the heart in all studies. Aortic incompetence was experienced during repeat infusion of cardioplegia in two studies and was corrected by releasing retraction on the heart and by manipulating the aortic root. Correct balloon position in the ascending aorta was confirmed with fluoroscopy in both these studies. Following closure of the left atrium and prior to deflating the balloon, the aortic root was vented via the central lumen of the balloon clamp. In one study blood was not initially able to be aspirated because of balloon migration into the aortic root which was confirmed by fluoroscopy. The balloon was partially deflated, withdrawn into the ascending aorta and reinflated with relief of obstruction to the tip of the catheter.

Sinus rhythm resumed spontaneously in four of six dogs following valve replacement, and two of six required internal defibrillation. All animals were weaned from bypass in sinus rhythm. The mean cardiac output was 6.5 ± 1.0 l/min preoperatively and 3.7 ± 0.36 l/min postoperatively. The corresponding PCWP’s were 4.0 ± 1.0 mmHg and 7.3 ± 2.4 mmHg. The mean gradient across the prosthetic mitral valve was 3.0 ± 2.2 mmHg. There was no ‘v’-wave evident on the PCWP tracing and no mitral regurgitation was seen on the left ventriculogram.

### 3.2. Retained intracardiac gas

Analysis of the effect of intrathoracic CO₂ on intracardiac gas retained after cardiotomy was made in the six dogs that had an MVR and the two dogs that had sham studies. At CO₂ inflow of 2 l/min, the intrathoracic CO₂ concentration was maintained between 86–98.5%. The arterial partial pressure of CO₂ was maintained at normal levels in all studies during CPB by adjusting oxygen flow through the oxygenator. The quantities of gas trapped in the aortic root vent bubble trap at the end of the study was 0.1 ± 0.1 ml in the CO₂ group, which was 8% of the volume caught in the non-CO₂ control group (1.3 ± 0.8 ml, *P* < 0.05).

### 4. Discussion

We have demonstrated in the dog the feasibility of mitral valve replacement via a right anterolateral minithoracotomy using a system for endovascular cardiopulmonary bypass and cardioplegia. The minimally invasive approach through the right chest provided good exposure of the mitral valve apparatus with minimal distortion. The peripheral cannulation system provided satisfactory CPB and myocardial protection. The method for de-airing the heart in the closed chest was reproducible and thorough and replicated methods used in open procedures. This approach has the potential to provide a superior cosmetic result and a reduction in the postoperative rehabilitation period.

Venous drainage must be sufficient to maintain adequate perfusion despite cardiac retraction to expose the
mitral valve. Via a sternotomy or right thoracotomy, bivacal cannulation is typically used when the interatrial septum is retracted to expose the valve, which may otherwise compromise the venous drainage. To overcome the need for separate caval cannulations for the minimally invasive technique we used a single large-bore femoral venous cannula with the tip positioned in the superior vena cava and augmented venous return with a centrifugal pump. We made a helical cut in the distal one third of this cannula to increase its flexibility: the spiral nature of the cut ensured the lumen did not collapse when septal retraction was used.

We found in the dog that a right lateral mini thoracotomy with minimal or no rib spreading provided excellent access for cardiac procedures and limited the number of intercostal incisions needed. Two or more instruments could be used through the minithoracotomy with less restriction than using multiple discrete ports, and surgery could be performed under direct vision. An innovation that we introduced to allow direct vision through the narrow horizontal port was to use a converging optical lens system which reduced the effective interpupillary distance to 10 mm and thus allowed stereovision of structures in the chest. A similar system has been used in ear nose and throat surgery.

Migration of the endoaortic clamp balloon is the main risk in this procedure and may cause arch vessel occlusion if the balloon moves cephalad, or loss of aortic occlusion, aortic incompetence or an inability to vent the left heart if it moves into the aortic root [6]. Endoclamp balloon migration into the root occurred in one study; the balloon was partially deflated and withdrawn to its correct position to allow venting and thus de-airing to occur. Aortic incompetence noted occasionally with repeat doses of cardioplegia in this study was resolved with adjustment of atrial retraction and external manipulation of the aortic root and was not related to balloon migration.

The preoperative cardiac outputs were high, and the post-valve replacement hemodynamics of all animals were satisfactory. Myocardial protection using endovascular bypass and cardioplegia has been shown to be equivalent to conventional techniques [7]. Retrograde cardioplegia was not used in this study but would be useful in the minimally invasive MVR procedure. A percutaneous coronary sinus cannula has been used for retrograde cardioplegia in the endovascular CPB system [6]. Alternatively a cannula could be placed in the coronary sinus through a purse-string suture in the right atrium.

Coronary air embolism from pooled intracardiac air can cause temporary regional wall motion abnormalities as detected by transesophageal echocardiography [8]. With the dog in a left lateral position and with the minimal atrial retraction required, blood filled from the apex (lowest point) to the atriotomy (highest point), displacing air passively. In the CO₂ group, a high percentage of CO₂ was consistently maintained in the chest cavity with low CO₂ inflow, and this further enhanced the efficacy of the de-airing procedure. Intrathoracic CO₂ had minimal effect on the ability to control arterial blood gases when on cardiopulmonary
bypass. The study design did not allow us to know the total volume of gas retained in the heart following atrial closure, and thus the percentage of total intracardiac air that was collected in the aortic root bubble trap was not known. The results however support the concept that CO₂ can be kept at a high concentration in the chest with a mini-thoracotomy and the risk of gas embolism can be significantly reduced. Carbon dioxide may be useful for minimal access cardiac surgery where aortic occlusion is not used and intracardiac repairs are done on the fibrillating heart. Further work is needed to determine if CO₂ can be beneficial in reducing the incidence of coronary artery air embolism. Trans-esophageal echocardiography was not used in this study but would provide additional information in determining the adequacy of de-airing. Aspiration of the left ventricular apex was not done in this study but could be achieved by passing a needle through the right ventricle and interventricular septum.

The dog had several features that may cause the method and results of this study to differ from clinical application. The ascending aorta in the greyhound was shorter and the aortic root larger than in man. This made secure endoclamp placement difficult. The cardiac axis was medial compared to humans and the mitral valve faced more posteriorly which made exposure from the right more difficult. The valve apparatus was normal and the chest narrower which made the implant simpler and quicker.

In summary the endovascular cardiopulmonary bypass system was effective in providing an arrested and protected heart. The endoaortic clamp made de-airing after cardiotomy safe and effective. A minimally invasive approach to achieve mitral valve replacement with cardioplegia is possible and convenient via a right minithoracotomy. A similar approach may also be useful when there is a relative contraindication to sternotomy such as intact coronary grafts, repeat mitral valve surgery, or anterior chest wall irradiation. Controlled clinical trials will determine the indications and contraindications for the various approaches.

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