The management of pulmonary atresia, ventricular septal defect, and multiple aorta pulmonary collateral arteries by definitive single stage repair in early infancy

Gary K. Lofland*

The Children's Mercy Hospital, University of Missouri Kansas City, 2401 Gillham Road, Kansas City, MO 64108, USA

Received 6 September 1999; received in revised form 26 May 2000; accepted 26 July 2000

Abstract

Objective: The management of infants and children with pulmonary atresia, ventricular septal defect, and multiple aorta pulmonary collateral arteries (PA/VSD/MAPCA) has proven to be challenging. Therapeutic approaches have included staged unifocalization, shunting, coiling of collateral vessels, and heart/lung transplantation. Results have been variable and frustrating. Hoping to take advantage of growth potential in pulmonary segments supplied by MAPCA, a more radical approach was adopted in March of 1997. This consists of single stage complete unifocalization with closure of the ventricular septal defect and establishment of right ventricular to pulmonary arterial continuity with a cryopreserved pulmonary allograft (Rastelli type correction) through a midline sternal incision. Methods: During an 18-month period, eleven consecutive infants with PA/VSD/MAPCA underwent complete surgical correction. The ages ranged from 5 days to 5 months. Weights ranged from 2.2 to 5.6 kg. Through a standard median sternotomy incision, the pericardium and both pleural spaces were opened. Normothermic cardiopulmonary bypass was instituted. Section of all collaterals was accomplished without hypoxemia, and all collaterals were ligated at their origin from the aorta. They were then brought through posterior mediastinum to construct a pulmonary artery confluence. The ventricular septal defect was closed, and continuity was established between the right ventricle and the newly created pulmonary artery confluence with cryopreserved allografts. Results: Ten of 11 patients survived operation, with postoperative courses that were uncomplicated. Length of stay ranged from 7±16 days, with a median length of stay of 11 days. One perioperative death occurred in a patient with preoperative co-morbidities of necrotizing enterocolitis, with no functioning gastrointestinal tract, intraventricular hemorrhage, and ventilator dependency since birth. At angiography, this patient has no demonstrable central pulmonary arteries and multiple diminutive aorta pulmonary collaterals. Autopsy revealed no demonstrable pulmonary arteries within the pulmonary parenchyma. All patients have been followed closely, and have grown normally. Two patients undergone repeat cardiac catheterization because of the echocardiographic demonstration of right ventricle pressures that had exceeded 50% of systemic. Both patients were treated with balloon angioplasty and one of these patients has had stenting of stenotic pulmonary arterial segments. No other patients have required additional hospitalization. Right ventricular pressures have remained less than fifty percent of systemic by echocardiographic assessment in all other patients. Conclusions: We feel that a single stage correction of pulmonary atresia, ventricular septal defect, and multiple aorta pulmonary collateral arteries can be accomplished in early infancy with acceptable morbidity and mortality. The initiation of normothermic cardio-pulmonary bypass greatly facilitates dissection of collaterals and prevents hypoxemia. Interventional cardiology with balloon angioplasty and stenting of abnormal pulmonary arterial segments is both an important essential adjunct in the management of these patients. We remain optimistic that a single stage approach to this complex lesion coupled with cardiac catheterization, balloon angioplasty, and stenting, will provide long-term results superior to staged approaches. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Pulmonary atresia; Pulmonary atresia with ventricular septal defect; Major aorta pulmonary collaterals; Unifocalization

1. Introduction

Pulmonary atresia (PA) with ventricular septal defect (VSD) and major aorta pulmonary collaterals (MAPCA) is a complex and rare lesion in which considerable morphologic variability exists regarding the sources of pulmonary blood flow. The true central pulmonary arteries range from a size approaching normal to complete absence. Major aorta pulmonary collaterals, probably derived embryologically from the splanchnic vascular plexus [1], are also highly variable in their size, number, course, origin, arborization, and histopathologic makeup [2–5]. A segment of lung may be supplied solely from the true pulmonary...
arteries, solely from the aorta pulmonary collaterals, or from both with connections between the two sources occurring at central or peripheral points and at single or multiple sites [4]. By contrast the intracardiac component of this defect is usually relatively straightforward, usually with a large anteriorly malaligned ventricular septal defect, a conotruncal type defect, well developed right and left ventricles with appropriate atrioventricular valves, and normal atrioventricular and ventriculoarterial connections.

The ultimate goal of surgical therapy is a biventricular correction. Definitive correction should include closure of the ventricular septal defect, closure of any interatrial communications, and establishment of continuity between a constructed pulmonary artery confluence and a right ventricle [6–9]. This has necessitated a series of staged unifocalizations in an attempt to build pulmonary arteries, followed by establishment of right ventricular to pulmonary artery continuity, with or without closure of the ventricular septal defect. This approach has generally required on average, approximately three separate operations [6–8]. Other individuals have taken a more aggressive approach in an attempt to achieve a single stage correction [10].

An important physiologic component of a favorable outcome is the post repair peak right ventricular pressure [6,11]. While obviously this should be low, it may depend greatly upon the pulmonary arterial and MAPCA morphology. The natural history of major aorta pulmonary collaterals includes progressive stenosis and occlusion, sometimes making any segment of lung supplied by these collaterals inaccessible or unusable if incorporated into definitive correction. Manipulation of these aorta pulmonary collaterals through attempts of unifocalization can produce iatrogenic occlusion in the form of scarring or anastomotic stenoses. Major aorta pulmonary collaterals without obstruction can lead to pulmonary vascular obstructive disease in the segment supplied by these collaterals. A single stage correction in early infancy before stenoses can occur, and before irreversible pulmonary vascular obstructive disease can occur, would logically be an ideal strategy for managing this otherwise frustrating condition. The earlier in life that the greatest number of healthy lung segments can be incorporated into the unifocalized pulmonary circulation, the more likely one is to capitalize upon the tremendous potential for additional growth and development of the pulmonary circulation and parenchyma that exists in early infancy.

2. Methods

Beginning in March of 1997 eleven consecutive infants with pulmonary atresia, ventricular septal defect and multiple pulmonary collateral underwent a single staged definitive correction. All diagnoses were established at birth or shortly thereafter, and all patients underwent cardiac catheterization at the time of initial diagnosis. Ages ranged from 5 days to 5.5 months with a mean and median age of three months. Weights ranged from 2.2 to 5.6 kg with a mean and median weight of 3 kg. None of the patients had undergone previous cardiac surgical procedures. The diagnosis was suggested by echocardiography and established definitively by cardiac catheterization with selective angiography. All collaterals were identified by selective angiography (Figs. 1 and 2).

Collaterals arose from the descending aorta in all patients. All collateral origins from the descending aorta were located anteriorly on the aorta and were within 4 cm from the origin of the left subclavian artery or distal aortic arch. The numbers of collateral origins from the aorta range from two to five. Collaterals also arose from the innominate or brachiocephalic trunk in two patients, and from the under surface of the aortic arch in three patients. In two patients collaterals branched shortly after arising from the proximal descending thoracic aorta to supply segments in both right and left lungs. All collaterals were quite tortuous.

If the diagnosis was made in the newborn period, the
patient was discharged shortly after birth and the repair was done electively in the first 2–3 months of life. One patient in whom major collaterals existed was rapidly developing severe unrelenting congestive heart failure and underwent complete correction at 5 days of age. A second patient was scheduled for repair at 2–3 months of age, but postponement was necessary because of respiratory syncytial viral infections. If patients had diminutive collaterals and central pulmonary arterial segments on initial cardiac catheterization, a second cardiac catheterization was performed at 2–3 months of age to assess growth of both collaterals and central pulmonary arterial segments. All patients had a single ventricular septal defect all of the malalignment type. All patients had atrial septal defects.

2.1. Technique

Through a standard midline incision, a median sternotomy and a subtotal thymectomy were performed. Both pleural spaces were opened widely just beneath the sternum and well anterior to the phrenic nerve. An attempt was made to dissect the collaterals prior to establishing cardiopulmonary bypass in all patients but was not successful in identifying all of the collaterals in any of the patients. Consequently, the strategy rapidly evolved of establishing normothermic cardio-pulmonary bypass with dual caval cannulation to allow for complete cardio-pulmonary decompression. This simple maneuver allowed for a much easier identification and dissection of collaterals, as both the heart and lungs could be manipulated to achieve better exposure of the posterior mediastinum. The posterior pericardium was incised between the superior vena cava and the aorta and the floor of the pericardial reflection and the transverse sinus was opened and the posterior mediastinal soft tissues dissected to expose the aortic segments and the collaterals in this region. The presence of a nasogastric tube or a tracheoesophageal echocardiographic probe also facilitated identification of posterior mediastinal structures. Opening the posterior mediastinal space also allowed for an avenue for rerouting collaterals so that the collaterals could be dissected along their entire length and all anastomoses accomplished under no tension. As the collaterals were very tortuous and extremely friable with consistently poor tissue quality, the dissection along their length was accomplished very carefully, to avoid disruption of the adventitia. The tortuosity of the collaterals, however, contributed to the ability to perform an anastomosis of the collaterals to either native pulmonary artery or pulmonary allograft without any tension on the length of the collaterals or the suture line. All collaterals were then permanently ligated at their origin, from the aorta usually using a single vascular clip. Since all collaterals were ligated while on cardio-pulmonary bypass, oxygenation was never in question. Following ligation, all collaterals were transected and unifocalization was accomplished with tissue to tissue anastomoses. Collaterals could be anastomosed to other collaterals or to the native pulmonary artery. Throughout the unifocalization process emphasis was on avoiding any synthetic or allograft materials in the periphery, and none were used in these patients. All anastomoses were accomplished using 7-0 Prolene suture on a fine needle (Ethicon, Somerset, NJ). Collaterals were anastomosed in the following manner:

1. Side to side anastomosis of the collateral to the central pulmonary arteries thereby augmenting the hypoplastic pulmonary arteries.
2. Side to side anastomosis of collateral to peripheral native pulmonary artery.
3. End to side anastomosis of collateral to collateral or collateral to native pulmonary artery.

An attempt was always made to bring as many collaterals as possible into as central a location as possible in an attempt to reconstruct a pulmonary artery confluence. Of note is that upon transection of the collateral at its origin, very little back bleeding was encountered. Clamping of the collateral itself was rarely if ever necessary.

Upon completion of unifocalization, the patient was then cooled to 22°C. The aorta was then cross-clamped and cardioplegic solution was given. A longitudinal ventriculotomy was then made in the right ventricular infundibulum and resection of hypertrophic muscle bundles was accom-
plished. The VSD was then closed with a Dacron sau­ge patch with a con­tinu­ous 5-0 Prolene suture. The right atrium was ope­ned to close the atri­al septal de­fect, leav­ing a small patent fora­men ovale. It was elected to leave a patent fora­men to func­tion as a ‘pop-off’ valve for systemic venous blood in the event of right ven­tri­cu­lar dys­func­tion or elev­ated right-sid­ed pres­sures. At this stage re­war­ming com­menced and the aortic cross-clamp was re­leased. A cryopre­served pul­mon­ary allograft was used in all cases to con­nect the right ven­tri­cle to the re­con­structed neu­ro­mam­mary arterial sys­tem. The dis­tal con­duit was an­asto­mosed to the re­con­structed pul­mon­ary arte­rial con­fluence using 6-0 Prolene. The prox­i­mal an­asto­mosis was ac­com­plished with 5-0 Prolene and if neces­sary, a prox­i­mal ex­ten­si­on uti­liz­ing ex­panded poly­tetrafluoroethylene (PTFE). The right atrium was then closed. Upon com­ple­tion of re­war­ming, the pa­tient was wea­ned from car­di­o-pul­mon­ary bypass. The du­ra­tion of car­di­o-pul­mon­ary bypass ran­ged from 119 to 160 min with a mean of 138 min. The du­ra­tion of the aortic cross clamp­ing was from 25 to 58 min with a mean of 32 min. Mod­i­fied ultra­filtration was per­formed in all pa­tients. Tran­se­sopha­geal echocar­di­og­ra­phy was per­formed in all pa­tients to as­sess the in­tegri­ty of the in­tra­car­diac repair, and to ob­tain an echocar­di­og­ra­phic as­sess­ment of right-sid­ed pres­sures. Tran­sthor­acic pres­sure mon­i­toring lines were not uti­lized in any pa­tient. Bilat­er­al pleural and me­diast­i­nal tubes were placed and the sternum was closed. Nitric oxide was avail­able for all pa­tients in the event right-sid­ed pres­sures were unac­cept­ably high, but was uti­lized in only one.

2.2. Follow-up

At dis­charge, all pa­tients had echo­car­di­og­ra­phy to as­sess right ven­tri­cu­lar per­for­mance and to as­sess right-sid­ed pres­sures. Ad­di­tion­al follow-up was ob­tained with­in 1–2 weeks of dis­charge and at mon­th­ly in­ter­vals for the next 6 mon­ths. Follow-up eval­ua­tion has been ac­com­plished in all pa­tients by di­rect pa­tient con­tact.

3. Results

3.1. Early results

Ten of 11 pa­tients sur­vived the in­itial op­er­a­tion. The length of stay post­oper­a­tively ran­ged from 7–16 days, with a med­i­an length of stay of ap­proxi­mately 11 days. Dur­a­tion of me­cha­nic­al ven­til­ation post­op­er­a­tively was 14–36 h, with a med­i­an du­ra­tion of me­cha­nic­al ven­til­ation of ap­prox­i­mately 18 h.

Min­i­mal in­trop­ic sup­port (dop­a­mine 5 μg/kg per min) was re­quired for a med­i­an du­ra­tion of 2 post­op­era­tive days. In­tra­ve­nous ni­tro­glycer­ine and ni­tro­prus­side were used in doses of 0.3 μg/kg per min. No pa­tients re­quired de­layed sternal clos­ure. Nitric oxide was avail­able on stand­by for all pa­tients, but was uti­lized for only one patient. The pa­tient in whom Nitric oxide was uti­lized was the one peri­op­er­a­tive death that oc­cu­rred in the series.

The one pa­tient who expired had sur­gery per­formed at 2.5 months of age. He had been in­tu­bated and me­chani­cally ven­til­ated since birth. He had expe­ri­enced comor­bi­dity of an in­tra­ven­tricular hem­or­r­age and se­vere nec­ro­tiz­ing en­terocol­i­tis. He had been main­tained on total pa­rental nu­tri­tion since birth. At car­di­ac cath­eter­iza­tion his aorta pul­mon­ary col­lar­al seg­ments were mul­ti­ple and dimin­u­tive. No cen­tral pul­mon­ary arte­ries were demon­strable by car­di­ac cath­eter­iza­tion. At au­topsy, he had no de­mon­strable pul­mon­ary arte­ries with­in the pul­mon­ary paren­chyma.

No pa­tients expe­rienced phren­ic nerve para­ly­sis and no chylo­thoraces oc­cu­rred. At dis­charge, all pa­tients un­der­went echocar­di­og­ra­phy. All pa­tients had right ven­tri­cu­lar pres­sures less than 50% of sys­temic. No pa­tients had res­i­dual ven­tri­cu­lar septal de­fects, and there was no more than trivial tricus­pid re­gur­gil­la­tion in all pa­tients. At dis­charge, the ar­te­rial o­xy­gen sa­tu­ra­tion in all pa­tients was greater than 95% on room air. No pa­tients re­quired sup­ple­men­tal oxygen fol­low­ing dis­charge.

3.2. Late results

All pa­tients have been fol­lowed at regular in­ter­vals. Two pa­tients have gra­du­ally evo­lved right ven­tri­cu­lar pres­sures of greater than 50% of sys­temic, and have un­der­gone re­peat car­di­ac cath­eter­iza­tion. Both of these pa­tients had sten­otic pul­mon­ary arte­rial seg­ments treated with bal­loon an­gi­oplasty with good re­sults (Fig. 3). One pa­tient re­quired stent­ing. All pa­tients have con­tin­ued to ex­pe­ri­ence nor­mal growth and de­vel­op­ment. Of note is that no pa­tients have re­quired rehos­pi­tal­iza­tion for any car­di­ac or non-car­di­ac causes, des­pite a par­tic­u­larly vir­u­lent sea­son with respira­tory syn­cy­tial vi­rus. No pa­tients in this se­ries have sub­se­quently de­vel­oped bron­cho­pul­mon­ary dys­plasia.

4. Discussion

Pul­mon­ary atresia with ven­tri­cu­lar septal de­fect rep­re­sen­tes an ex­treme form of tetro­logy of Fallot [12]. It may oc­cur as an iso­lated le­sion or as part of a genet­ic syn­drome [13]. Re­cent stud­ies have doc­u­mented that tetro­logy of Fallot with pul­mon­ary atresia be­longs to a spec­trum of conotrunc­nal car­di­ac ma­lforma­tions that are of­ten as­so­ci­ated with monosom­y 22q11 [14]. The clinical pre­sen­ta­tion of monosom­y 22q11 in­cludes pa­tients with conotrunc­nal anom­a­ly face syn­drome, velo­car­di­o-fa­cial syn­drome and Di­George syn­drome [15,16]. More re­cently these syn­dromes have been in­cor­po­rated as a group un­der the ac­ronym CATCH 22 (car­di­ac de­fect, ab­nor­mal face, thy­mic hypopla­sia, cleft palate, hy­pocal­ce­mia, and mi­cro dele­tion 22q11 [17]). Two groups have re­cently de­mon­strated an as­so­ci­ation be­tween pa­tients with pul­mon­ary atresia, ven­tri­cu­lar septal de­fect, and major aorta pul­mon­ary col­lar­al arte­ries and monosom­y 22q11 [12,18]. In both stud­ies,
anywhere from 40 to 48% of patients with pulmonary atresia, ventricular septal defect, and major aorta pulmonary collateral where shown to have a micro deletion in 22q11 [12,18].

Pulmonary atresia with ventricular septal defect and major aorta pulmonary collaterals is uncommon however comprising only about 25% of all cases of pulmonary atresia and ventricular septal defect [6]. In this defect there is an absolute deficiency of central pulmonary artery, with most of the pulmonary parenchyma being supplied by major aorta pulmonary collaterals. The systemic hemodynamic and morphologic studies of the collateral supply in this lesion have been accomplished by McCartney and Associates [19], Haworth [20], Haworth and colleagues [21], Thiene and co-workers [22], and Rabinovitch and associates [5]. The concept of unifocalization of multiple sources of vascular supply to the lungs in an attempt to establish a pulmonary arterial confluence was suggested by Haworth and McCartney [4].

The results with the staged approach of unifocalization have been extremely variable [6–9,23]. In all series reviewed, total repair was accomplished in 12–60% of patients. These series also do not take into account attrition occurring prior to surgical intervention, or exclusion of patients who are deemed unsuitable for any intervention. It is felt that only 20–30% of a cohort of newborn infants with this combination of anomalies will have complete repair with acceptable right ventricular hemodynamics if a delayed stage approach is taken [10].

In 1995, Reddy, Liddicoat and Hanley demonstrated that by using a one-stage approach through a mid-line sternal incision, it was possible to achieve a complete correction [10]. In their series of ten patients ranging in age from 1.43 months to 37.34 years, complete correction was achieved in all patients. Although delayed closure of the ventricular septal defect was felt to be occasionally necessary, it was felt by these investigators that definitive correction could be accomplished at an early age. These investigators speculated that ideally, correction should be accomplished between 3 and 6 months of age. In the present series, both the mean and median age of correction was 3 months as opposed to a median age of correction of 2.08 years and a mean age of correction of 5.96 years.

Although Nakata index has been discussed extensively [24], we did not employ Nakata index in this series of patients. It was our feeling the definitive repair could be accomplished at quite an early age; consequently, no patients who were referred were excluded.

Some authors have advocated bilateral thoracotomies with a transsternal (clamshell) approach [25]. We did not find it necessary to utilize this approach. We also did not find it necessary to modify in any way our standard sternotomy incision.

In conclusion, complete unifocalization of all sources of pulmonary blood supply, an intracardiac repair of pulmonary with ventricular septal defect in major aorta pulmonary collaterals, can be accomplished in a single stage through a standard median sternotomy incision. The repair can be accomplished with acceptable morbidity and mortality, with a length of hospital stay that is not excessive. Mid-term follow-up results reveal excellent hemodynamics and functional status. Balloon angioplasty has been accomplished with good results, and stenting of stenotic segments remains an important therapeutic adjunct.

We do, however, feel that patient selection will ultimately prove to be very important. Although this was a consecutive patient series, one patient in this series experienced no growth whatsoever of his aorta pulmonary collaterals between birth and the time of operation, and had no central pulmonary arteries demonstrable anatomically. Only
References


Appendix A. Conference discussion

Mr M. Pozzi (Liverpool, UK): I have two questions for you: (1) do you think there is any difference between the patients with MAPCAs only? My impression is that patients with pulmonary arteries on which MAPCAs can be anastomosed on have a much better prognosis after this type of repair. (2) Although I fundamentally agree with your approach, at the moment I would recommend a complete, single stage repair at 2–3 months of age only in patients with unrestricted flow through the MAPCAs, while I would delay to between 12 and 24 months of age when the MAPCAs present several stenosis. I would appreciate your comments on this approach.
I think regarding the age of correction, we are still in a little bit of uncharted territory, since most of these patients historically have been corrected at older ages.

Dr A. Corno (Lausanne, Switzerland): At the poster presentation of this morning, the Japanese group of Osaka presented very good results with a pericardial roll to reconstruct the pulmonary arteries continuity. They left the pericardial roll in an unusual position, anterior to the aorta and the vena cava, and they claim no compression of this conduit. Since from the angio it seems that you leave your reconstruction of the pulmonary artery posterior to the aorta, do you believe that the anterior position could reduce the need for postoperative dilatation or stent because of obstruction of the pulmonary arteries?

And a second question, since you leave everything behind the aorta usually, how can you prevent or reduce the incidence of bronchial compression with the new reconstructed pulmonary artery?

Dr Lofland: In answer to the first question, I don’t know if bringing the conduit in a different position will reduce the incidence of either branch stenosis or a conduit obstruction. I don’t have an answer to that. We simply chose to put ours in a more anatomic location, and we had no technical difficulty in achieving that. I also expected these patients to manifest some degree of tracheobronchial malacia at about 5-6 months of age, and we have been pleasantly surprised in that none of these patients who have undergone an early correction have demonstrated any degree of tracheobronchial malacia. I have always associated that with pulmonary atresia also. We had not experienced that in this series, though.

Dr G. Stellin (Padova, Italy): We all enjoyed your presentation, obviously. Frank Hanley in his original presentation at the AATS in Boston in 1995 showed us that he approaches the collateral vessels through the transverse sinus. You said to us you are approaching the collaterals through the right or left pleural space. Can you tell us what are the advantages to do that?

Dr Lofland: In the paper that came out of that presentation, Dr Hanley did mention that he opened both pleural spaces to facilitate direct dissection, and that is very necessary. We also open up the posterior pericardium, the transverse sinus posteriorly, and that really does facilitate the bringing up of these collaterals through that space to perform the pulmonary artery confluence reconstruction.

Dr Stellin: So, your approach is both through the transverse sinus and left pleural space?

Dr Lofland: Yes, I could not reach all of the collaterals to the posterior leaf through the transverse sinus, and I found early on in this series that I simply had to open the pleural spaces, decompress the lungs completely, and that way the lungs could be actually moved out of the operative field, which greatly facilitates dissection.

Dr H. Uemura (Osaka, Japan): Recently, our preference is a one-stage repair, as you say, in patients with MAPCAS, but in our series a third of such patients could undergo a one-stage repair and the remaining two thirds of our patients could not undergo a one-stage repair because of complete absence or very vestigial nature of the central pulmonary arteries. Do you think in all patients you can establish a one-stage repair?

Dr Lofland: No, I don’t, and I think we demonstrated that with the one perioperative death in our series. That patient had collaterals that were minuscule and no pulmonary arteries that had developed over the two and a half months of that patient’s life. I think that the prognosis for that patient was fairly dismal. In embarking upon this series, though, we did not deny this kind of approach to any patient who presented.