Journal of Veterinary Cardiology (2019) **25**, 32—40

Journal of Veterinary Cardiology ESVC

www.elsevier.com/locate/jvc

Cardiovascular Methods and Techniques

Dilatable pulmonary artery banding for ventricular septal defect: surgical technique and case report of three cats☆

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Received 9 May 2019; received in revised form 22 July 2019; accepted 20 August 2019

KEYWORDS
Feline;
Congenital heart defect;
Pulmonary artery band;
Surgery

Abstract Pulmonary artery banding (PAB) is a viable but underreported palliative option for hemodynamically significant ventricular septal defect in small animals. A significant challenge associated with PAB is judging the degree of band tightening, which can be further complicated when animals are immature and still growing at the time of PAB. If a pulmonary artery band is overtightened or becomes progressively too tight after surgery, the result can be reversal of shunt flow with potentially devastating consequences. Placement of a band that could be percutaneously dilated using a balloon catheter affords a minimally invasive option for partially or completely relieving the band should it become too tight after PAB. This report describes a surgical technique for placement of a dilatable pulmonary artery band, reviews guidelines for tightening the band, and reports the outcome of three cats undergoing the procedure. All three cats showed evidence of reduced hemodynamic load after PAB for a period of up to three years after PAB.

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https://doi.org/10.1016/j.jvc.2019.08.001
1760-2734/

Abbreviations:

2-D	two-dimensional
CHF	congestive heart failure
LA	left atrium
LA:Ao	left atrium-to-aortic dimension ratio
LV	left ventricle
LVIDd	left ventricular internal diameter at end-diastole
PA	pulmonary artery
PAB	pulmonary artery banding
PAP	pulmonary arterial pressure
PDA	patent ductus arteriosus
PG	pressure gradient
Qp:Qs	pulmonary-to-systemic flow ratio
RV	right ventricle
SAP	systemic arterial pressure
VSD	ventricular septal defect
VSD:Ao	ventricular septal defect-to-aortic diameter ratio

Pulmonary artery banding (PAB) is a recognized but sometimes overlooked option for palliation of ventricular septal defect (VSD). Because options for definitive repair of VSD are limited, PAB can be considered for long-term palliation of hemodynamically significant VSD. A significant challenge associated with PAB is judging the optimal degree of band tightening, which can be further complicated when animals are immature at the time of PAB. If a pulmonary artery (PA) band is overtightened or becomes progressively too tight after surgery, the result can be reversal of flow through the VSD with potentially devastating consequences. Thus, a technique that allows the band to be dilated percutaneously after PAB has advantages over the traditional technique. This report describes a surgical technique for dilatable PAB and reports outcome in three cats undergoing surgery.

Surgical technique

Surgery is performed through a left fourth intercostal thoracotomy. The pericardium is incised parallel and ventral to the phrenic nerve and sutured to the incision site to expose the PA trunk (Fig. 1A). The loose adventitial tissue connecting the PA to the ascending aorta is sharply incised with scissors cranially and caudally. Right-angle forceps are passed between the PA and ascending aorta to grasp and pull a 4-mm-wide band of polytetrafluoroethylene around the PA (Fig. 1B). A partial-thickness pledget-reinforced mattress or purse-string suture of 5-0 or 6-0 polypropylene is placed in the PA distal to the band and passed through a tourniquet (Fig. 1C). A 22-gauge over-the-needle catheter is placed into the PA and secured to the tourniquet to measure pulmonary artery pressure (PAP) distal to the band during band tightening. The band is progressively tightened with a series of hemostatic clips (Fig. 1D). The primary guidelines for band tightening are to decrease systolic PAP distal to the band toward normal (30 mmHg) and to increase systemic arterial pressure (SAP) until a plateau is reached [1]. Other guidelines that can be considered are the velocity and direction of VSD flow measured by epicardial or transesophageal Doppler echocardiography [2] and measurement of pulmonary artery oxygen saturation distal to the band [3]. Once the band is appropriately tightened, a mattress suture of 6-0 polypropylene is placed in the band at the level of the last hemostatic clip (Fig. 1E). The pericardium is closed loosely with interrupted sutures. A thoracostomy tube is placed, and the thoracotomy incision is closed.

Case reports

Case 1

A 12-week-old domestic short-haired cat (1.6 kg) was presented for evaluation of a cardiac murmur. A grade V/VI systolic heart murmur was heard with a right parasternal border point of maximal intensity. Echocardiography confirmed a perimembranous VSD with a diameter of 1.9 mm (Fig. 2). The aortic annulus measured 4.1 mm resulting in a VSD-to-aortic diameter ratio (VSD:Ao) of 0.46. Flow through the VSD was left to right with a Doppler-measured peak velocity of 3.7 m/s and an estimated left ventricular (LV)-to-right ventricular (RV) pressure gradient (PG) of 56 mmHg. The pulmonary-to-systemic flow ratio (Qp:Qs) was estimated at 2.4 based on pulsed-wave Doppler measurement of pulmonary and aortic velocity time integrals and cross-sectional areas [4]. The left atrium (LA) was considered moderately dilated based on a two-dimensional (2-D) left atrium-to-aortic dimension ratio (LA:Ao) of 1.94 (reference range: 0.85—1.40) [5]. The LV was

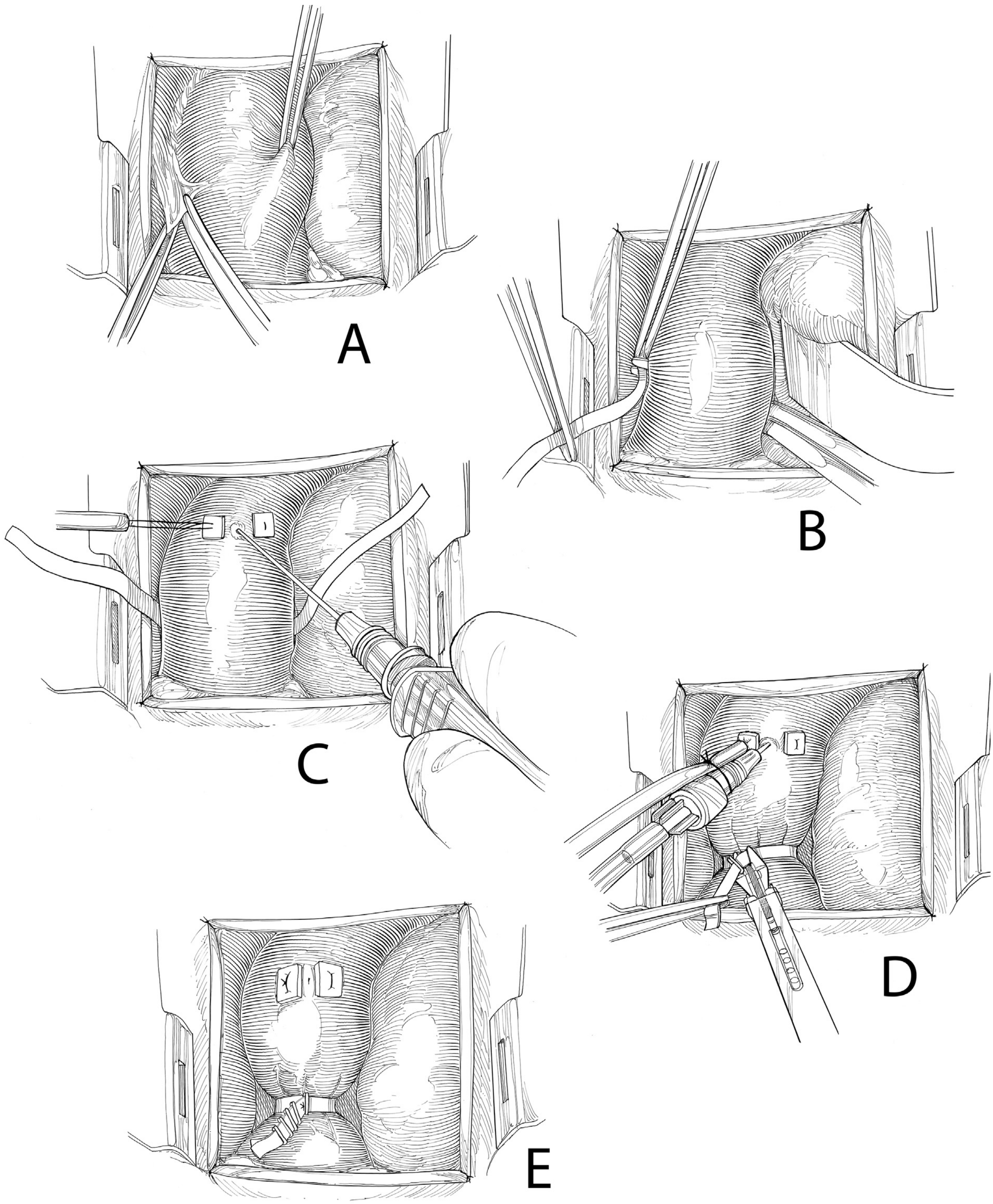

Fig. 1 Illustration of surgical technique. (A) Separation of the pulmonary artery (PA) trunk from the aorta by sharp dissection. (B) The left auricle is retracted caudally. Right-angle forceps are passed medial to the PA to grasp a band of polytetrafluoroethylene. The band is pulled around the PA. (C) A buttressed mattress suture is placed distal to the band and through a Rommel tourniquet. An over-the-needle catheter is placed inside the mattress suture and connected to the pressure monitor. (D) The tourniquet is cinched and secured to the catheter. The band is progressively tightened by placing successive hemoclips while monitoring distal pulmonary arterial and systemic arterial pressures. (D) Once optimal pressures are achieved, the catheter is removed and the mattress suture is tied. The band is additionally secured by placing an interrupted suture of 6-0 polypropylene just above the deepest hemoclip.

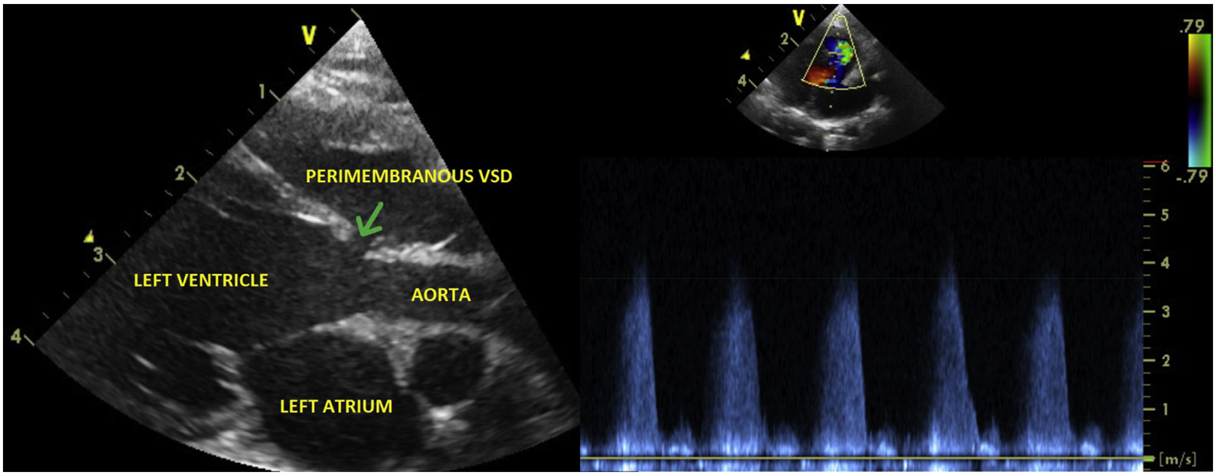

Fig. 2 Echocardiographic images of a 12-week-old male domestic short-haired cat (case 1) performed before pulmonary artery banding. The right parasternal inflow outflow view shows a perimembranous VSD measuring 4.1 mm in diameter, which is 46% the diameter of the aortic annulus. Moderate left atrial and left ventricular dilation are noted. Continuous-wave Doppler flow profile of the VSD shows a peak velocity of 3.7 m/s, which is consistent with a calculated pressure gradient of 56 mmHg. VSD, ventricular septal defect.

considered dilated for a cat of this size and age based on an internal diameter of the LV at end-diastole (LVIDd) of 15 mm (reference range: 9.2–13.3 mm) [6]. Moderate concentric thickening of the RV free wall was present with early diastolic flattening of the interventricular septum. Peak systolic velocity across the pulmonary valve was not measured because of turbulence in the RV outflow tract.

The VSD was judged to be hemodynamically significant based on VSD:Ao, estimated Qp:Qs, and the presence of left heart remodeling. The cat underwent PAB with a dilatable band as described previously. Systolic/diastolic SAP increased from 77/55 mmHg before to 100/82 mmHg after PAB. Systolic PAP was 24 mmHg after PAB.

Echocardiographic examinations were performed at 3, 12, 24, and 36 months after PAB. Echocardiographic examination at 36 months showed left-to-right flow across the VSD with a peak velocity of 2.6 m/s and an estimated LV-to-RV PG of 27 mmHg. A hyperechoic band was apparent on the PA with accelerated flow across the band (Supplemental Video I). The peak velocity of flow across the band was 4.2 m/s with an estimated PG of 70 mmHg. There was mild LA enlargement based on a 2-D long-axis LA:Ao of 2.1 and 2-D short-axis LA:Ao of 1.61 [7]. Left ventricular chamber size was normal for an adult cat (7.6 kg) based on an LVIDd of 18.6 mm (reference range: 8.8–18.9) [8]. Left ventricular fractional shortening was 62%. Trace aortic insufficiency was observed. Mild-to-moderate RV concentric hypertrophy was noted. Normal sinus rhythm was observed throughout study. The cat was alive without clinical signs 40 months after PAB.

Case 2

A 10-month-old male domestic short-haired cat (4.1 kg) was referred for PAB. At approximately 12 weeks of age, the cat was diagnosed with VSD and congestive heart failure (CHF). Medications at presentation were furosemide 6.25 mg PO q 12 h and enalapril 2.5 mg PO q 12 h. A grade V/VI right parasternal systolic murmur was present. Generalized cardiomegaly with severe LA enlargement and marked overcirculation of the pulmonary vessels were found on thoracic radiography (Fig. 3). There was a moderate, diffuse interstitial pattern. Standard 2-D echocardiography revealed a perimembranous VSD with a diameter of 4 mm. The diameter of the aortic annulus measured 7.9 mm, resulting in a VSD:Ao of 0.56. Flow through the VSD was left to right with a peak velocity of 3.9 m/s and an estimated LV-to-RV PG of 61 mmHg. Pulsed-wave Doppler evaluation of aortic and pulmonary flow resulted in an estimated Qp:Qs of 2.1. Left atrial enlargement was considered severe with a 2-D LA:Ao of 2.7. The LV was severely dilated with an LVIDd of 26.2 mm and normal wall thicknesses.

Based on echocardiographic evidence of a hemodynamically significant VSD and presence of medically controlled CHF, PAB was performed according to the technique described previously (Supplemental Video II). Just before PAB, systolic/diastolic SAP and PAP were 85/68 mmHg and 68/

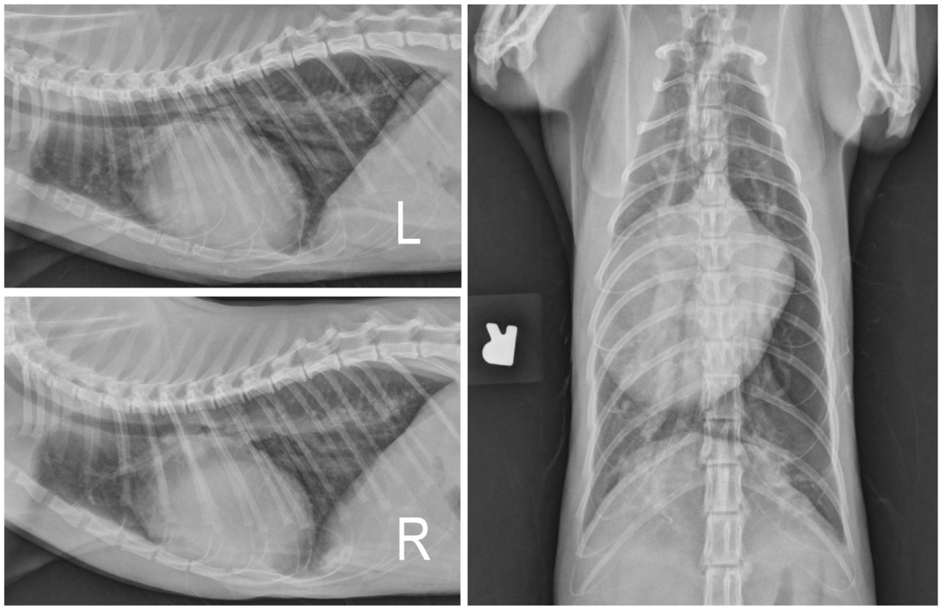

Fig. 3 Thoracic radiographs (right lateral, left lateral, and VD projections) from a 10-month-old male intact domestic short-haired cat (case 2) show severe cardiomegaly and marked pulmonary overcirculation secondary to the ventricular septal defect. A diffuse bronchointerstitial pattern is present consistent with cardiogenic pulmonary edema. VD, ventral dorsal.

50 mmHg, respectively. After PAB, systolic/diastolic SAP and PAP were 117/99 mmHg and 41/38 mmHg, respectively. Postprocedural echocardiogram one day after PAB showed a decrease in the peak velocity across the VSD at 3.0 m/s with an estimated PG of 37 mmHg (Fig. 4). The PA peak velocity at the level of the band was 3.5 m/s with

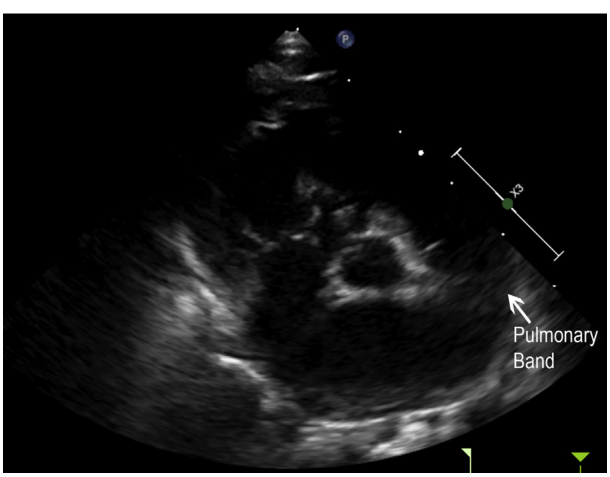

Fig. 4 Echocardiographic image of a 10-month-old male intact domestic short-haired cat (case 2) one day after pulmonary artery band placement. Right parasternal short-axis view at the level of the aorta and pulmonary valve shows a hyperechoic structure (arrow) causing mild narrowing of the main pulmonary artery just distal to the pulmonary valve at the location where the pulmonary band was placed.

an estimated PG of 50 mmHg (Supplemental Video III). The cat was discharged one day after surgery with a recommendation to discontinue furosemide and continue enalapril at 2.5 mg PO q 24 h. Follow-up evaluations were performed at 0.5, 4, and 6 months by the referring cardiologist. At 6 months after PAB, flow velocity across the VSD was 3.4 m/s with an estimated LV-to-RV PG of 47 mmHg. Velocity across the PA band measured 4.3 m/s with an estimated PG of 75 mmHg. Subjective 2-D assessment showed a moderately dilated left atrium and an LVIDd of 24 mm. The patient had gained weight and was judged to be normally active. Enalapril was continued at 2.5 mg PO q 24 h. The patient was alive without clinical signs at 9 months after PAB.

Case 3

A 4-week-old domestic short-haired cat (0.8 kg) was presented for evaluation of a loud cardiac murmur, resting tachypnea, and activity intolerance. Grade V/VI systolic and continuous heart murmurs were heard at the right parasternal border and left cardiac base, respectively. The respiratory rate was 140 breaths per minute. Echocardiography revealed a left-to-right shunting perimembranous VSD and patent ductus arteriosus (PDA). The VSD diameter was 2.5 mm, and the aortic annulus diameter was 4.9 mm, resulting in a VSD:Ao of 0.51. Velocity of the VSD flow was likely underestimated but appeared to reflect increased RV pressure with maximal systolic flow of 2.0 m/s (estimated LV-to-RV PG of 16 mmHg). The Qp:Qs was estimated to be 1.8 based on pulsed-wave Doppler evaluation. Pulmonary artery velocities were normal at 1.1 m/s. Moderate-to-severe LA enlargement was noted with a 2-D right parasternal short-axis LA:Ao of 1.95. The LV was considered dilated for a kitten (LVIDd = 17.6 mm; ref range 5.8–11.9 mm) [7]. There was mild pulmonary and tricuspid valve insufficiency with peak TR velocity of 3.0 m/s, suggesting mild pulmonary hypertension. There was trace pleural effusion and lung reverberation artifact consistent with pulmonary edema. Sinus tachycardia was noted throughout the examination.

Based on evidence of severe volume overload and CHF associated with PDA and VSD, the cat underwent surgical ligation of the PDA and placement of a PA band. Because of the additive left-to-right shunts and young age of the cat, it was elected to close the PDA and place, but not tighten, the PA band. The rationale was to decrease the total shunt load by closing the PDA and allow the cat to 'grow into' the PA band. Follow-up echocardiographic evaluations were performed at 0.5, 1, 2, 4, and 5 months after surgery. Postoperative and follow-up echocardiograms confirmed successful PDA ligation with no residual flow. At 5 months after surgery, Doppler-measured peak velocity across the VSD was 3.6 m/s and peak velocity across the pulmonary artery band was 2.5 m/s (estimated PG of 52 and 25 mmHg, respectively). The left atrial and ventricular sizes were measured as LA:Ao of 1.4 (2-D short-axis) and LVIDd of 17.7 mm, respectively. The cat had a normal activity level with no clinical signs related to CHF at 9 months after PAB. Cardiac medications had been discontinued.

Discussion

Pulmonary artery banding was first described by Muller and Danimann in 1952 [9] as a palliative operation for children with large left-to-right shunt secondary to VSD or single ventricle, both to slow progression of pulmonary hypertension and control CHF. In 1989, Kron et al. [10] reported the results of 170 children undergoing PAB between 1958 and 1988 (100 children were operated before 1970). The actuarial survival at ten years for these children was 92%. Currently, PAB is reserved for sick children or children with more complex congenital heart defects such as multiple VSD, complete atrioventricular septal defects, double-inlet ventricle, and double-outlet ventricle without pulmonary valve stenosis [1]. The first report of PAB in a cat with VSD and CHF was by Sheridan et al. [11] in 1971. In 1977, Eyster et al. [12] reported the first case series in five dogs and one cat with VSD and CHF. The guideline for tightening the PA band was to reduce the PA to about one-third of its original diameter. Five of six animals survived surgery. One dog died shortly after surgery due to reversal of shunt flow across the VSD. The remaining four animals received significant palliation for periods of up to seven years. In 2018, Dos Santos et al.[a] reported outcomes in four cats and one pony undergoing PAB. The guidelines for PA band tightening were not reported. All animals were reported to be free of CHF or right-to-left shunt for a median period of 3.5 years (range: 2–9.8 years). Perhaps because of a paucity of reports documenting outcomes in animals, PAB can be overlooked as a viable option for animals with hemodynamically significant VSD. The favorable outcomes of the three cats in this report provide further evidence of the viability of PAB as a palliative treatment for hemodynamically significant VSD.

Intervention is indicated for hemodynamically significant VSD to prevent or delay onset of CHF and/or progressive pulmonary hypertension. Several parameters suggest that a VSD is hemodynamically significant, including radiographic evidence of pulmonary vascular enlargement, radiographic or echocardiographic evidence of left atrial and ventricular remodeling, lower-than-predicted spectral Doppler-measured shunt flow velocity across the defect, and/or elevated peak pulmonary flow velocity. Classically, intervention is based on Qp:Qs determined by echocardiography or oximetry. Based on guidelines in human infants, Qp:Qs < 1.5 suggests that a VSD is restrictive and argues against the need for intervention [1]. Similarly, favorable prognosis has been reported for dogs and cats with Qp:Qs < 1.5 [4]. A Qp:Qs > 2.0 indicates a large left-to-right shunt and is generally an indication for intervention. The VSD:Ao has been reported to correlate with Qp:Qs in dogs and cats [4]. A VSD:Ao < 0.4 is associated with a favorable prognosis. All of the cats in this report had VSD:Ao > 0.4 and estimated Qp:Qs > 1.5.

[a] Dos Santos LF, Scollan KF, LeBlanc NL, Milovancev M, Townsend KL, Huber MJ. Long-term Outcomes of Pulmonary Artery Banding for Ventricular Septal Defects, ACVIM Abstracts 2018, p 2170.

The goal of PAB is to increase RV systolic pressure and thus decrease the PG driving shunt flow across the VSD. The procedure effectively transfers a portion of the overload on the LV to the RV, trading a measure of LV volume overload for RV pressure overload. The hazard of PAB is overtightening the band and reversal of shunt flow. Thus, a critical aspect of PAB is the determination of how tight to make the band. The classic guidelines for tightening the band are based on PAP measured distal (downstream) to the band and SAP. In the case of VSD, the aim is to reduce the PAP distal to the band to close to normal systolic pressure of 30 mmHg [6]. As the PA band is tightened, the SAP starts to rise as the systolic PAP falls. Optimal band tightening in children is aimed at achieving a 10—20 mmHg increase in SAP without bradycardia or a decrease in arterial oxygen saturation below 90% [1]. Another guideline that has been considered is a decrease in PA oxygen saturation (indicating less volume of oxygenated blood shunting to the right side) [3]. Finally, an additional subjective guideline that we have used in previous cases is to decrease the shunt velocity toward but not below approximately 2.8 m/sec (estimated PG of 30 mmHg) measured by intraoperative epicardial or transesophageal Doppler echocardiography [2].

For animals that are immature at the time of PAB, growth adds an additional challenge to determination of optimal band tightness at the time of surgery. Beyond estimating the amount of expected growth, there are few measureable guidelines. It is thus prudent to remain conservative during band tightening to avoid overtightening as the patient grows. Typically an appropriate band in a mature animal reduces the diameter of the PA by about two-thirds. Thus, it might be considered that the reduction in PA diameter should be less than two-thirds in an immature animal. Placement of a dilatable band provides a measure of safety should the band become too tight as the animal grows. Two of the cats in this case report were immature at the time of PAB. In both cases, tightening of the band was more conservative. In fact, in case 3, the PA band was placed but not tightened. Both cats have now reached maturity without the need to loosen the band. Nevertheless, placement of a dilatable PA band in these cases at least theoretically added a degree of safety to the procedure.

Several methods for producing a dilatable PA band have been described including banding with absorbable suture [13], securing the band with 6-0 suture [14], and securing the band with hemostatic clips [15]. The technique reported here uses hemostatic clips to incrementally tighten the band, followed by a final fixation of the band with 6-0 suture. We now use this technique for all animals undergoing PAB. So far, none of the cats in this report have required percutaneous balloon dilation of their PA band. Thus, we have not yet demonstrated that PA bands placed with this technique will be dilatable in animals. In a recent report of 28 children undergoing balloon dilation of PA bands placed using this technique, 27 underwent successful partial or complete reversal of banding for periods of up to 2.2 years after PAB [16]. In one child in this series undergoing balloon dilation three years after PAB, high-pressure balloon dilation was unable to relieve pulmonary stenosis associated with the PA band, suggesting that bands placed using this technique may not remain dilatable indefinitely. A theoretical advantage of this technique is that it is possible to incrementally dilate the band depending on the degree of reversal needed.

In conclusion, despite a paucity of case reports in animals, PAB remains a viable option for short- and possibly long-term palliation of hemodynamically significant VSD in cats. Placement of a dilatable PA band is feasible in immature and mature cats and offers at least the possibility of percutaneous partial or complete reversal of band tightening should it become necessary.

Conflict of Interest Statement

The authors do not have any conflicts of interest to disclose.

Acknowledgement

The authors thank Molly Borman, MS, for illustrations of the surgery (http://www.mborman.com/). The authors also thank Dr. Justin Thomason for referral and follow-up care of case 2.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jvc.2019.08.001.

Video table

Video	Title	Description
I	Echocardiogram 3 years after pulmonary artery banding (Case 1)	Echocardiographic images from a 3-year-old male DSH (Case 1) performed 3 years after pulmonary artery (PA) band placement. Right parasternal inflow outflow views show a left-to-right shunting perimembranous ventricular septal defect. Right parasternal short axis view of the ventricles at the level of the chordae tendineae shows preserved left ventricular systolic function and mild-to-moderate right ventricular concentric hypertrophy with moderate septal flattening in systole and diastole. Right parasternal short axis view of the pulmonary valve shows a hyperechoic structure (white arrow) causing narrowing of the PA distal to the pulmonary valve. Color flow Doppler shows aliasing of the color signal at the level of the PA band. Continuous wave Doppler flow profile shows an elevated PA velocity at the level of the PA band of 4.2 m/s with calculated pressure gradient of 70 mmHg.
II	Pulmonary artery banding surgery (case 2)	After a standard left 4th intercostal thoracotomy, the pericardium was opened to expose the pulmonary artery (PA) trunk. The loose connective tissues between the PA and ascending aorta were incised. A right-angle forceps was passed medial to the PA and used to grasp a polytetrafluoroethylene band. The band was brought around the PA. Prior to tightening, a mattress suture was placed distal to the band and through a Rommel tourniquet. An over-the-needle catheter was introduced into the PA and connected to a pressure-monitoring device. The band was progressively tightened while monitoring hemodynamic parameters. A quad view shows the operative field (top left), pulmonary arterial pressure distal to the band (top right), anesthesia monitor with invasive systemic arterial pressure (bottom right), and the operating room (bottom left). As the PA band was tightened, the pulmonary arterial pressure decreased and systemic arterial pressure increased to a plateau. The PA band was secured with a single interrupted suture of 6-0 polypropylene just above the deepest hemoclip.
III	ost-operative echocardiogram after pulmonary artery banding (Case 2)	Echocardiographic images from a 10-month-old male intact DSH (Case 2) performed one-day after pulmonary artery (PA) band placement. A left-to-right shunting perimembranous ventricular septal defect is visualized on right parasternal long axis and short axis views. Aneurysmal tissue is noted at the location of the ventricular septal defect on the right parasternal short axis view. Continuous wave Doppler flow profile shows a reduction in flow velocity across the ventricular septal defect to 3.0 m/s compared to the pre-operative velocity measured at 3.9 m/s. A hyperechoic structure (arrow) is present distal to the pulmonary valve narrowing of PA in the region of the PA band. Continuous wave Doppler flow profile shows an elevated PA velocity at the level of the band of 3.5 m/s compared to the pre-operative PA velocity of 1.35 m/s.
IV	Pre-operative echocardiogram (Case 3), Echocardiographic images from a 4-week-old male intact cat (Case 3)	Right parasternal 4-chamber view shows moderate-to-severe left atrial and left ventricular dilation and moderate right ventricular concentric hypertrophy. Right parasternal inflow-outflow views show a left-to-right shunting perimembranous ventricular septal defect, which measures 2.5 mm in diameter (51% the diameter of the aortic annulus). Right parasternal short axis view shows preserved left ventricular systolic function and moderate right ventricular concentric hypertrophy with mild septal flattening. Right parasternal short axis view of the aorta and left atrium shows aneurysmal tissue at the location of a perimembranous ventricular septal defect, left-to-right shunt, and mild tricuspid insufficiency. Right parasternal short axis view of the aorta and pulmonary artery shows left-to-right flow entering the pulmonary artery in the region of a patent ductus arteriosus.

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