Open surgical repair of tetralogy of Fallot in dogs

E. Christopher Orton, DVM, PhD, DACVS; Khursheed Mama, DVM, DACVA; Peter Hellyer, DVM, MS, DACVA; Timothy B. Hackett, DVM, MS, DACVECC

Tetralogy of Fallot is a complex congenital heart defect characterized by **right ventricular outflow tract (RVOT)** obstruction, **ventricular septal defect (VSD)**, dextropositioned and overriding aorta, and right ventricular hypertrophy. Tetralogy of Fallot is the most important cyanotic heart defect in dogs and accounts for approximately 4% of cardiac malformations in dogs overall.[1] The defect occurs in several breeds of dog, including Keeshond, Poodle, Miniature Schnauzer, Beagle, English Bulldog, Collie, Shetland Sheepdog, and several terrier breeds.[1,2]

The pathophysiologic consequences of tetralogy depend on the magnitude of RVOT obstruction. With severe RVOT obstruction, the defect allows right-to-left shunt of blood from the right ventricle through the VSD into the systemic circulation. The results are hypoxemia, cyanosis, progressive polycythemia, debilitating weakness and exercise intolerance, and shortened life span.

Surgical palliation of tetralogy of Fallot by creation of a systemic-to-pulmonary shunt has been described in dogs.[2,3] Long-term palliation of tetralogy of Fallot by these shunts has not been demonstrated in dogs. Definitive open surgical repair is considered the only viable long-term treatment for this defect in human children.[4] This report describes the technique for definitive open surgical repair of tetralogy of Fallot in dogs. The intermediate-term outcome of 2 severely affected dogs that underwent this correction is reported.

Technique

Anesthesia and monitoring—Dogs were medicated with atropine (0.03 mg/kg [0.014 mg/lb] of body weight, SC) or glycopyrrolate (0.01 mg/kg [0.005 mg/lb], SC), oxymorphone (0.05 mg/kg [0.023 mg/lb], SC) or morphine (0.5 mg/kg, SC), and midazolam (0.2 mg/kg [0.09 mg/lb], SC). Anesthesia was induced with fentanyl (6 to 12 µg/kg [2.7 to 5.5 µg/lb], IV) with or without etomidate (0.5 mg/kg, IV). Balanced anesthesia was maintained by inhalation of isoflurane, infusion of fentanyl citrate (20 to 45 µg/kg/h [9 to 20 µg/lb/h], IV), and intermittent administration of atracurium besylate (0.1 to 0.25 mg/kg [0.045 to 0.11 mg/lb], IV). Phenylephrine (1 to 2 µg/kg/min [0.45 to 0.9 µg/lb/min], IV) was administered as needed to maintain systemic blood pressure and decrease right-to-left shunt prior to the repair. Esmolol (100 µg/kg/min [45 µg/lb/min], IV) was administered as needed to control dynamic RVOT obstruction prior to the repair. Positive pressure ventilation was maintained throughout the procedure except during full cardiopulmonary bypass. During this period, isoflurane was administered via a vaporizer placed in the gas line supplying the membrane oxygenator. Dexamethasone sodium phosphate (1 mg/kg [0.45 mg/lb], IV) was administered prior to cardiopulmonary bypass. Cefoxitin (22 mg/kg [10 mg/lb], IV) was administered every 90 minutes during surgery.

A 7-F triple-lumen catheter was placed percutaneously into a jugular vein to provide central venous access and monitor **central venous pressure (CVP)**. A dorsal pedal arterial catheter was placed to monitor direct arterial pressure and for arterial blood gas analysis. The ECG, arterial blood pressure, CVP, end-tidal CO_2, and esophageal and rectal temperatures were monitored continuously during surgery. Arterial and venous blood gases, **activated clotting time (ACT)**, concentrations of sodium, potassium, ionized calcium, Hct, and total protein were measured periodically throughout the procedure.

Cardiopulmonary bypass—Dogs were positioned in dorsal recumbancy for cardiopulmonary bypass and surgery. Prior to cannulation for cardiopulmonary bypass, heparin sulfate (3 mg/kg [1.4 mg/lb], IV) was administered to achieve complete anticoagulation (ACT, > 480 seconds). The left femoral artery was surgically exposed through an inguinal incision and a straight arterial cannula (8- to 12-F) placed in the artery.[5] The heart and great vessels were exposed through a median sternotomy. The pericardium was opened on its ventral midline and secured with sutures to the sternotomy. Purse-string sutures[a] were placed in the right atrial appendage and cranial vena cava. A straight venous cannula was introduced into the right atrium through the right atrial appendage and then advanced into the caudal vena cava.[5] An angled venous cannula was introduced directly into the cranial vena cava. A left ventricular vent was introduced through a pledget-buttressed[b] mattress suture in the left ventricular apex. Cardiopulmonary bypass was initiated by diverting blood from the right heart to the cardiopulmonary bypass circuit by means of the venous cannulae.

The primary bypass circuit consisted of a roller pump, membrane oxygenator,[c] reservoir,[d] heat exchanger, and circulating heater/cooler water bath. The heater/cooler water bath was used to control body temperature by means of a heat exchanger built into the primary circuit. Blood in the operative field is salvaged and returned to the reservoir by 2 suction lines driven by additional roller pumps. During cardiopulmonary bypass, blood entering the left ventricle was returned to the reservoir by means of a vent cannula and line. The arterial line, vent line, and suction lines

From the Department of Clinical Sciences, College of Veterinary Medicine and Biomedical Sciences, Colorado State University, Fort Collins, CO 80523.

were constructed from 0.25-in tubing and connectors, whereas the venous side of the bypass circuit was constructed of 0.375-in tubing and connectors.

The bypass circuit was primed with balanced pH-adjusted (7.4) crystalloid solution.[e] Additives to the crystalloid prime were mannitol (0.5 mg/kg [0.22 mg/lb] of body weight), sodium bicarbonate (15 mg/L of prime), and heparin (1,000 U/L of prime). Dogs were hemodiluted by mixing their blood volume with the circuit prime and cooled to a rectal temperature of 28 C (82.4 F). The magnitude of hemodilution was dependent on the degree of polycythemia prior to surgery. Perfusion flows were 50 to 80 ml/kg/min (22.7 to 36.4 ml/lb/min), depending on body temperature. Phenylephrine (0.05 to 0.1 mg/kg [0.022 to 0.045], IV) was administered periodically to increase vascular resistance and maintain mean arterial pressure above 50 mm Hg during cardiopulmonary bypass. Metabolic acidosis during cardiopulmonary bypass was corrected by administration of sodium bicarbonate (0.5 to 1 mEq/kg [0.22 to 0.45 mEq/lb]) into the bypass circuit.

A cannula was introduced through a buttressed mattress suture in the ascending aorta for administration of cardioplegia solution.[5] The ascending aorta was cross-clamped, and complete cardiac arrest was achieved by administration of a cold cardioplegia solution (15 ml/kg [6.8 ml/lb]) into the coronary circulation via the aortic cannula. Administration of cardioplegia solution was repeated every 20 minutes to maintain cardiac arrest. Cardioplegia solution consisted of balanced pH-adjusted (7.4) crystalloid solution[e] with added potassium chloride (100 mEq/L for initial dose, 50 mEq/L all subsequent doses), sodium bicarbonate (50 mEq/L), mannitol (3 g/L), and lidocaine (100 mg/L). Heparinized blood from the bypass circuit was added to the crystalloid cardioplegia solution at 4:1 (crystalloid:blood) to make the final sanguineous-crystalloid cardioplegia solution.

After cardiac incisions were closed, the aortic cross-clamp was removed, and coronary circulation was reestablished. The heart was electrically defibrillated if necessary with direct current (20 to 50 J), using internal paddles. Dogs were warmed to 38 C [100.4 F] and gradually weaned from cardiopulmonary bypass. During this period, calcium chloride (10 mg/kg [4.5 mg/lb], IV) was administered to keep the pH-corrected ionized calcium between 1.0 and 1.2 mmol/L. Inotropic support with dobutamine (1 to 10 µg/kg/min [0.45 to 4.5 µg/lb/min], IV) or epinephrine (0.05 to 0.5 µg/kg/min [0.023 to 0.23 µg/lb/min], IV) was administered as necessary to support systemic blood pressure and cardiac output. After discontinuation of cardiopulmonary bypass, residual blood volume in the reservoir was returned via the arterial line until the CVP was between 4 and 10 mm Hg. Once the dog had been weaned from cardiopulmonary bypass and was hemodynamically stable, cannulae were removed in the reverse order that they were introduced, and protamine sulfate (0.8 to 1.2 mg/mg of heparin, IV) was administered slowly (10 to 15 minutes) to reverse the anticoagulation. Fresh whole blood (1 unit) was administered after protamine administration was complete.

Cardiac repair—The cardiac repair was accomplished through an incision in the right ventricle that spanned the region of the RVOT obstruction (**Fig 1**). The location of the obstruction was determined by preoperative echocardiography and visual inspection at surgery. The ventriculotomy incision was extended across the pulmonic valve annulus into the main pulmonary artery, depending on whether the RVOT obstruction included a valvular pulmonic stenosis component. If necessary, a fibromuscular band or infundibular hypertrophy was partially excised, taking care to avoid injury to the papillary apparatus of the tricuspid valve. The perimembranous VSD was identified below the crista supraventricularis adjacent to the tricuspid valve. Buttressed mattress sutures were preplaced around the circumference of the VSD, taking care not to pass sutures full-thickness through the margin of the defect to avoid injury to conduction tissues and aortic valve leaflets. In the area where the defect was bordered by the annulus of the septal tricuspid leaflet, mattress sutures were passed through the valve annulus from the atrial side of the valve. Mattress sutures were passed through a round **polytetrafluoroethylene (PTFE)** cardiovascular patch,[f] the patch was seated into the defect, and the sutures were tied. The ventriculotomy (and pulmonary arteriotomy) was closed by imposition of an oval-shaped PTFE cardiovascular patch,[f] using a simple continuous suture pattern. The patch-graft was reinforced with buttressed mattress sutures as necessary.

Results

Surgical repair for tetralogy of Fallot was undertaken in 2 dogs. One was a 3-month-old male 12-kg [26.4-lb] shepherd mixed-breed dog, and the other was a 12-month-old spayed female 13-kg [28.6-lb] shepherd mixed-breed dog. Right ventricular hypertrophy, perimembranous VSD, RVOT obstruction, and dextropositioned overriding aorta were demonstrated on echocardiography in both dogs. Right-to-left shunting of blood at rest was evident on Doppler echocardiography. Both dogs were moderately to severely affected during normal activity. One dog was only mildly cyanotic at rest but became intensely cyanotic and tachypneic after brief periods of activity (eg, walking or playing). The Hct was 41%. This dog was thought to have a dynamic form of RVOT obstruction that worsened right-to-left shunting of blood during activity. The RVOT obstruction in this dog was found to consist of a discrete muscular band below the pulmonic valve with a normal pulmonic valve. In this dog, the fibromuscular band was partially excised, and the RVOT patch-graft was extended across the area of obstruction but not across the pulmonic valve annulus. The other dog had severe cyanosis at rest, polycythemia (Hct, 79%), and was intolerant of even mild physical activity (eg, eating, standing). This dog underwent phlebotomy and crystalloid fluid replacement therapy prior to surgery (1 and 4 weeks) to decrease polycythemia. The RVOT obstruction in this dog was characterized by pulmonic valve dysplasia (ie, thickened immobile valve leaflets and hypoplastic annulus). In this dog, the right ventriculotomy was extended across the pulmonic annulus into

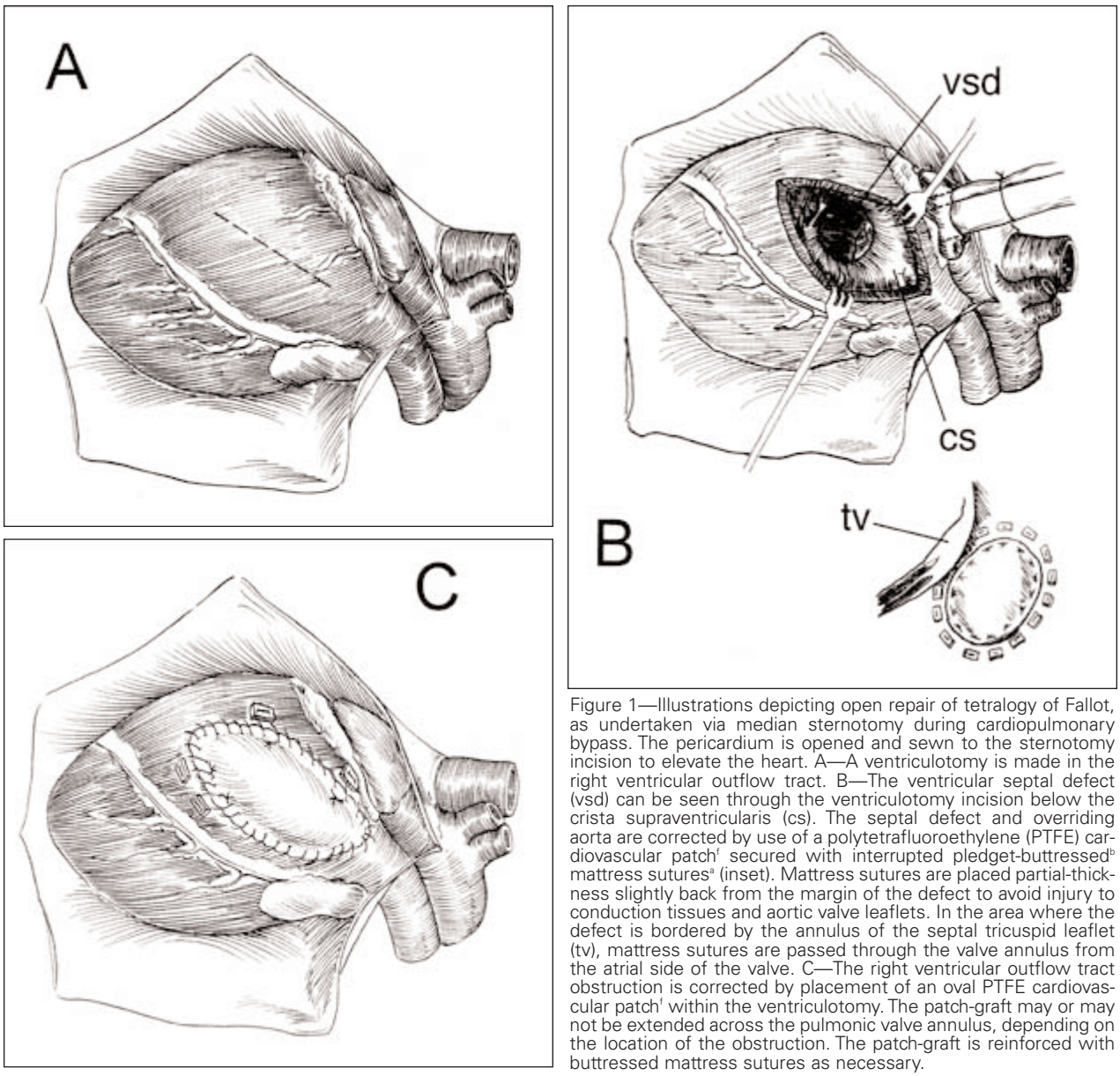

Figure 1—Illustrations depicting open repair of tetralogy of Fallot, as undertaken via median sternotomy during cardiopulmonary bypass. The pericardium is opened and sewn to the sternotomy incision to elevate the heart. A—A ventriculotomy is made in the right ventricular outflow tract. B—The ventricular septal defect (vsd) can be seen through the ventriculotomy incision below the crista supraventricularis (cs). The septal defect and overriding aorta are corrected by use of a polytetrafluoroethylene (PTFE) cardiovascular patch[f] secured with interrupted pledget-buttressed[b] mattress sutures[a] (inset). Mattress sutures are placed partial-thickness slightly back from the margin of the defect to avoid injury to conduction tissues and aortic valve leaflets. In the area where the defect is bordered by the annulus of the septal tricuspid leaflet (tv), mattress sutures are passed through the valve annulus from the atrial side of the valve. C—The right ventricular outflow tract obstruction is corrected by placement of an oval PTFE cardiovascular patch[f] within the ventriculotomy. The patch-graft may or may not be extended across the pulmonic valve annulus, depending on the location of the obstruction. The patch-graft is reinforced with buttressed mattress sutures as necessary.

the main pulmonary artery, and the RVOT was reconstructed with a transannular patch-graft. This dog required electrical defibrillation after removal of the aortic cross-clamp.

Both dogs survived open surgical repair for tetralogy of Fallot and were immediately improved (ie, not cyanotic) after surgery. Supportive care after surgery consisted of administration of crystalloid fluids (2.2 ml/kg/h [1 ml/lb/h], IV), frozen plasma (IV, PRN to keep CVP > 4 mm Hg), lidocaine (70 µg/kg/min [32 µg/lb/min], IV), fentanyl (2 to 4 µg/kg/h [0.9 to 1.8 µg/lb/min], IV), and cefoxitin (22 mg/kg [10 mg/lb], IV, q 8 h). In 1 dog, supplemental oxygen (4 L/min) was administered by nasal catheter for 8 hours after surgery. In the other dog, a tracheostomy was performed, and ventilator therapy was administered for 14 hours after surgery because of persistent hypoxemia (PaO_2, < 70 mm Hg) with supplemental oxygen alone. Ventilator therapy consisted of pressure-supported (5 to 8 cm H_2O) spontaneous ventilation with positive end-expiratory pressure (6 cm H_2O) and a 0.8 fraction of inspired oxygen. Dogs were given aspirin (20 mg, PO, q 24 h) and atenolol (0.5 to 1.0 mg/kg [0.23 to 0.45 mg/lb], PO, q 12 h) for 3 months, beginning on the third day after surgery. Both dogs achieved normal activity levels and exercise tolerance within a few weeks after surgery. Dogs were alive and apparently clinically normal at 36 and 24 months after surgery, respectively. One dog competed in agility trials after surgery.

Discussion

The natural history and life expectancy of human children with unrepaired tetralogy of Fallot is so clearly inferior to that of children undergoing surgical repair that there has been little debate about whether reparative surgery should be undertaken.[4] The only debate has

evolved around the timing of definitive surgical repair.[4,6-10] The natural history and life expectancy of dogs with tetralogy of Fallot depend on the severity of RVOT obstruction. Dogs with clinical signs of severe RVOT obstruction are likely to succumb to the effects of severe hypoxemia and polycythemia, usually before 1 year of age.[2] Less severely affected dogs may be able to tolerate the defect for several years but remain moderately to severely exercise intolerant. Less-affected dogs often have progression of RVOT obstruction and worsening of clinical signs over time. The older (12-month-old) dog in this report had severe clinical signs and was polycythemic; it likely would not have survived more than a few weeks without surgery. The younger (3-month-old) dog was less affected at the time of surgery but had documented progression of RVOT obstruction and worsening right-to-left shunt in the weeks prior to surgery. It was also believed that this dog had an unfavorable long-term prognosis without surgery. Definitive surgical repair corrected the underlying physiologic anomaly responsible for hypoxemia in the dogs reported here. As a result, surgery resolved the clinical signs of disease and restored normal exercise tolerance in these dogs. Whether these dogs will have an ongoing or diminishing risk for sudden cardiac death after the repair cannot be determined from this report.

The surgical correction reported here is based on the standard repair for uncomplicated tetralogy of Fallot in human children.[4] The right ventriculotomy approach provided good exposure for repair of the VSD in both dogs. The ventriculotomy was then incorporated into the reconstruction of the RVOT. In human infants with tetralogy of Fallot, RVOT obstruction may or may not involve the pulmonic valve annulus. In the former instance, the ventriculotomy incision is extended across the pulmonic annulus into the main pulmonary artery, and the RVOT is reconstructed with a transannular patch. In the latter instance, the RVOT may be reconstructed without extending the repair across the pulmonic valve. Interestingly, both variations of the repair were represented in the 2 dogs reported here. A transannular reconstruction was required for 1 dog in this report but not the other. No apparent difference in the outcome between these dogs was noticed.

Definitive surgical repair for tetralogy of Fallot has been reported previously in 2 dogs.[11,12] In 1 report,[11] the dog was cyanotic, exercise intolerant, and mildly polycythemic at the time of surgery. Surgical repair for this dog consisted of patch closure of the VSD through a right ventriculotomy similar to the technique in this report. Relief of RVOT obstruction was attempted by partial excision of hypertrophied infundibular muscle and obturator dilation of the pulmonary valve. The ventriculotomy was closed primarily without reconstruction of the RVOT to preserve pulmonic valve competence. The dog had resolution of cyanosis but developed signs compatible with right-sided congestive heart failure within 4 weeks after surgery. Cardiac catheterization 1 year after surgery confirmed residual RVOT obstruction. The dog died unexpectedly 2 years after surgery. Although the cause of right heart failure and death was not determined in this dog, the case likely illustrates the importance of RVOT reconstruction in successful repair of tetralogy of Fallot. Preservation of pulmonic valve competence is not considered an important goal in tetralogy repair as isolated pulmonic insufficiency is generally not associated with heart failure unless pulmonary vascular resistance is increased.[13] In the other report,[12] the dog undergoing repair did not have overt clinical signs of disease and had left-to-right shunt at rest at the time of surgery. Repair of the VSD in this dog was accomplished by direct closure with buttressed mattress sutures without a patch through a separate right atriotomy approach. The RVOT was reconstructed with a transannular patch of autogenous pericardium. The dog remained free of clinical signs of disease after surgery.

Several systemic-to-pulmonic shunts have been devised for surgical palliation of tetralogy of Fallot, including the Blalock Taussig (subclavian-to-pulmonary artery anastomosis), Potts (aorticopulmonary anastomosis), Waterston (aorta-to-right pulmonary artery anastomosis), and Glenn (vena caval-to-pulmonary arterial anastomosis) shunts.[14] The physiologic rationale for these shunts is to increase pulmonary blood flow and thereby decrease the relative fraction of venous admixture and degree of hypoxemia. Historically, systemic-to-pulmonary shunts were used for long-term palliation of tetralogy of Fallot in human patients before definitive correction became available. Symptomatic improvement was observed in 85% of patients for as long as 20 years after surgery.[15] In humans, these shunts have been largely abandoned in favor of early definitive repair during infancy for uncomplicated tetralogy of Fallot.[4] Systemic-to-pulmonary shunts have been advocated for long-term palliation of tetralogy of Fallot in dogs. Unfortunately, the limited reports available have not indicated effective long-term palliation for most dogs undergoing systemic-to-pulmonary shunt procedures.[2,3]

In conclusion, open surgical repair of tetralogy of Fallot, based on the standard repair in humans, is feasible in severely affected dogs and results in complete resolution of clinical signs associated with the defect.

[a]Ti-Cron, Davis & Geck, American Cyanamid Co, Danbury, Conn.
[b]TFE Polymer Pledget, Davis & Geck, American Cyanamid Co, Danbury, Conn.
[c]COBE Optimin hollow fiber membrane oxygenator, COBE Cardiovascular Inc, Arvada, Colo.
[d]COBE HVR 2200 filtered hardshell venous reservoir, COBE Cardiovascular Inc, Arvada, Colo.
[e]Plasma-Lyte A pH 7.4, Baxter Healthcare Corp, Deerfield, Ill.
[f]GORE-TEX cardiovascular patch, WL Gore & Associates Inc, Flagstaff, Ariz.

References

1. Buchanan JW. Prevalence of cardiovascular disorders. In: Fox PR, Sisson D, Moïse NS, eds. *Textbook of canine and feline cardiology.* 2nd ed. Philadelphia: WB Saunders Co, 1999;457–470.

2. Ringwald RJ, Bonagura JD. Tetralogy of Fallot in the dog: clinical findings in 13 cases. *J Am Anim Hosp Assoc* 1988; 24:33–43.

3. Eyster GE, Braden TD, Appleford M, et al. Surgical management of tetralogy of Fallot. *J Small Anim Pract* 1977; 18:387–394.

4. Castaneda AR, Mayer J. Tetralogy of Fallot. In: Stark J, de Leval M, eds. *Surgery for congenital heart defects.* 2nd ed. Philadelphia: WB Saunders Co, 1994;405–416.

5. Orton EC. Cardiopulmonary bypass. In: Bojrab MJ, ed.

Current techniques in small animal surgery. Baltimore: The Williams & Wilkins Co, 1998;679–688.

6. Castaneda AR, Freed MD, Williams RG, et al. Repair of tetralogy of Fallot in infancy: early and late results. *J Thorac Cardiovasc Surg* 1977;74:372–381.

7. Garson A, Gorry GA, McNamara DG, et al. The surgical decision in tetralogy of Fallot: weighing the risks and benefits with decision analysis. *Am J Cardiol* 1980;45:108–116.

8. Pacifico AD, Bargeron LM, Kirklin JW. Primary total correction of tetralogy of Fallot in children less than four years of age. *Circulation* 1973;68:1085–1091.

9. Richardson JP, Clarke CP. Tetralogy of Fallot: risk factors associated with complete repair. *Br Heart J* 1976;38:926–933.

10. Rittenhouse EA, Mansfield PB, Hall DG, et al. Tetralogy of Fallot: selective staged management. *J Thorac Cardiovasc Surg* 1985; 89:772–779.

11. Herrtage ME, Hall LW, English TAH. Surgical correction of the tetralogy of Fallot in a dog. *J Small Anim Pract* 1983; 24:51–62.

12. Lew LJ, Fowler JD, McKay R, et al. Open-heart correction of tetralogy of Fallot in an acyanotic dog. *J Am Vet Med Assoc* 1998; 213:652–657.

13. Pacifico AD, Kirklin JK, Colvin EV, et al. Tetralogy of Fallot: late results and reoperations. *Semin Thorac Cardiovasc Surg* 1990;2:708–716.

14. de Lavel M. Systemic-to-pulmonary artery shunts. In: Stark J, de Leval M, eds. *Surgery for congenital heart defects.* 2nd ed. Philadelphia: WB Saunders Co, 1994;247–257.

15. Cole RB, Muster AJ, Fixler DE, et al. Long-term results of aortopulmonary anastomosis for tetralogy of Fallot: morbidity and mortality, 1946–1969. *Circulation* 1971;63: 263–271.

Correction: Plasma concentration of ionized calcium in healthy iguanas

In Table 1 in the article "Plasma concentration of ionized calcium in healthy iguanas" (*J Am Vet Med Assoc* 2001;219:326–328), 2 ranges are incorrect. The range for total protein concentration in adults should be 2.4 to 6.8 units, and the range for albumin concentration in adults should be 1.8 to 4.7 units.