Truncus arteriosus repair: A 40-year multicenter perspective

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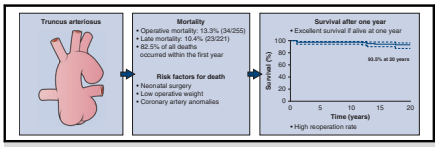
ABSTRACT

Objective: To examine the long-term surgical outcomes of patients who underwent truncus arteriosus (TA) repair.

Methods: Between 1979 and 2018, a total of 255 patients underwent TA repair at 3 Australian hospitals. Data were obtained by review of medical records from initial admission until last cardiology follow-up.

Results: At the time of TA repair, the median patient age was 44 days, and median weight was 3.5 kg. Early mortality was 13.3% (34 of 255), and overall survival was 76.8 ± 2.9% at 20 years. Neonatal surgery and low operative weight were risk factors for early mortality. Most deaths (82.5%; 47 of 57) occurred within the first year following repair. A coronary artery anomaly and early reoperation were identified as risk factors for late mortality. A total of 175 patients required at least 1 reoperation, with overall freedom of reoperation of 2.9 ± 1.5% at 20 years. Follow-up of survivors was 96% complete (191 of 198). The median duration of follow-up was 16.4 years. At the last follow-up, 190 patients were categorized as New York Heart Association class I/II, and 1 patient was class III.

Conclusions: TA repair during the neonatal period presents significant surgical challenges. Neonates with signs of overcirculation should be operated on promptly. A coronary artery anomaly is a risk factor for late mortality. Survival beyond the first year following repair is associated with excellent outcomes. (J Thorac Cardiovasc Surg 2021;161:230-40)



Risk factors and outcomes following truncus arteriosus repair.

CENTRAL MESSAGE

Neonates and coronary anomalies pose significant challenges to truncus arteriosus repair. Survival beyond the first year is associated with excellent outcomes.

PERSPECTIVE

Neonatal repair of truncus arteriosus still poses significant surgical challenges, particularly in the presence of concomitant anomalies or truncal valve insufficiency. It is likely that patients with moderate truncal valve insufficiency will require truncal valve surgery. Patients surviving to 1 year after complete repair generally have excellent long-term survival.

See Commentaries on pages 241 and 242.

Truncus arteriosus (TA) is a rare and complex congenital cardiac anomaly associated with significant morbidity and mortality. Early mortality for TA is 3% to 20%, depending on perioperative status and the presence of concomitant anomalies.[1-14] The reported long-term survival after TA repair is approximately 75% at 20 years.[1-14] There are few large cohort studies reporting the long-term outcomes of these complex patients; therefore, we sought to determine the long-term surgical outcomes of patients who underwent TA repair at 3 Australian institutions that have a similar approach to TA repair.

METHODS

Data were obtained by review of medical records from the initial admission until last cardiology follow-up at The Royal Children's Hospital, Melbourne; Queensland Children's Hospital, Brisbane; and The Prince

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Abbreviation and Acronym
TA = truncus arteriosus

Charles Hospital, Brisbane. The Royal Children's Hospital Human Research Ethics Committee and the Children's Health Queensland Hospital and Health Service Research Governance approved the study design.

Between 1979 and 2018, 255 consecutive patients underwent TA repair and were included in the study. Patient characteristics are summarized in Table 1. Twenty patients underwent 1 or more surgical procedures before TA repair; these included pulmonary artery banding (n = 12), pulmonary artery reconstruction (n = 4), major aortopulmonary collateral artery ligation (n = 3), modified Blalock–Taussig shunt (n = 2), interrupted aortic arch repair (n = 2), and tracheoesophageal fistula repair (n = 2). Most patients (16 of 20; 80%) who had previous surgical procedures presented before 1998. Seventy-eight patients required admission to the intensive care unit (ICU) before TA repair, 2 of whom required extracorporeal membrane oxygenation.

Definitions

Early mortality and reoperation were defined as those occurring within 30 days of surgery or before hospital discharge. All other deaths and reoperations were considered late. A modified Van Praagh classification for TA was used.[15]

Data Analysis

Data analyses were performed using Stata 14 (StataCorp, College Station, Tex). Continuous data are expressed as mean ± standard deviation (range), and skewed continuous data are expressed as median (range). Categorical data are summarized as frequency and percentage. The χ^2 test, Student's *t* test, and Mann–Whitney *U* test were used as appropriate. Univariable and multivariable logistic regression and Cox proportional hazard modeling were used to determine risk factors for mortality and reoperation. A stepwise forward selection model was used to create the multivariable models. Variables with significance in the univariable model at threshold of $P = .2$ and variables previously shown to impact the outcome of interest were selected. The likelihood ratio test was used on the addition and subtraction of variables to assess benefit to the model. With regard to Cox proportional hazard modeling, the proportional hazard assumption was tested and shown to be valid for the outcomes described. Kaplan–Meier survival curves were used to analyze and plot time-related endpoints. The log-rank test was used to compare survivor functions. Statistical significance was set at $P < .05$.

TABLE 1. Patient characteristics (N = 255)

Characteristic	Value
Neonates, % (n/N)	36.5 (93/255)
Male sex, % (n/N)	54.5 (139/255)
Age at repair, median (range)	44 d (range, 1 d to 8.7 y)
Weight at repair, kg, median (range)	3.5 (range, 1.2-23.0)
Classification, % (n/N)	
Type 1	61.6 (157/255)
Type 2	26.7 (68/255)
Type 3	11.0 (28/255)
Unspecified	0.8 (2/255)
Truncal valve anatomy, % (n/N)	
Bicuspid	10.6 (27/255)
Tricuspid	58.0 (148/255)
Quadricuspid	30.2 (77/255)
Truncal valve insufficiency, % (n/N)	
None	54.9 (140/255)
Mild	29.8 (76/255)
Moderate	11.8 (30/255)
Severe	2.4 (6/255)
Syndromes, % (n/N)	21.2 (54/255)
DiGeorge syndrome	15.3 (39/255)
Other syndromes	4.7 (12/255)
Concomitant anomalies, % (n/N)	
ASD	32.5 (83/255)
PDA	21.2 (54/255)
Aortic arch obstruction	14.1 (36/255)
IAA	12.9 (33/255)
Type A	21.2 (7/33)
Type B	72.7 (24/33)
Type C	6.1 (2/33)
CoA	1.2 (3/255)
Coronary artery anomaly	10.6 (27/255)
MAPCA	3.1 (8/255)
AVSD	0.4 (1/255)
TAPVD	0.4 (1/255)

ASD, Atrial septal defect; *PDA*, patent ductus arteriosus; *IAA*, interrupted aortic arch; *CoA*, coarctation of aorta; *MAPCA*, major aortopulmonary collateral artery; *AVSD*, atrioventricular septal defect; *TAPVD*, total anomalous pulmonary venous drainage.

RESULTS

Surgical Data

At the time of TA repair, the median patient age was 44 days (range, 1 day to 8.7 years) and the median weight was 3.5 kg (range, 1.2-23.0 kg). The median age at repair was 81.5 days (range, 1 day to 8.7 years) between 1979 and 1988, 68.5 days (range, 3 days to 1.9 years) between 1989 and 1998, 31 days (range, 2 days to 2.0 years) between 1999 and 2008, and 21 days (range, 1 day to 3.1 years) between 2009 and 2018 ($P < .001$). Surgery was performed via midline sternotomy with cardiopulmonary bypass in all patients. The pulmonary arteries were detached from the TA, and continuity between the right ventricle and pulmonary artery was established via a conduit (n = 239) or direct anastomosis (n = 16) of the main pulmonary artery to the right ventricle, with or without a monocusp valve. Concomitant cardiovascular surgery at TA repair included atrial septal defect closure in 93 patients, aortic arch reconstruction in 34 patients, pulmonary artery reconstruction in 23 patients, coronary artery repair in 5 patients, major aortopulmonary collateral artery ligation in 4 patients, placement of an aortopulmonary shunt in 1 patient, and total anomalous pulmonary venous drainage repair in 1 patient. The median cardiopulmonary bypass time was 133 minutes (mean, 150 minutes; range, 33-439 minutes), and the median aortic cross-clamp time was 75 minutes (mean, 86 minutes; range, 31-263 minutes).

TABLE 2. Risk factors for mortality

Risk factor	Mortality, % (n/N)	Univariable		Multivariable regression	
		OR (95% CI)	*P* value	OR (95% CI)	*P* value
Early mortality					
Moderate TVI	20.0 (6/30)	1.8 (0.7-4.8)	.238		
Severe TVI	33.3 (2/6)	3.5 (0.6-19.7)	.161		
AA obstruction	27.8 (10/36)	3.1 (1.3-7.3)	.008	1.7 (0.6-4.3)	.299
Coronary anomaly	22.2 (6/27)	2.0 (0.8-5.5)	.158		
Preoperative ICU	20.5 (16/78)	2.3 (1.1-4.7)	.028		
Neonate	23.7 (22/93)	3.9 (1.8-8.3)	<.001	2.9 (1.3-6.8)	.012
Low weight (<2.5 kg)	41.2 (7/17)	5.5 (1.9-15.6)	.001	4.0 (1.3-12.1)	.013
TV surgery	18.2 (6/33)	1.5 (0.6-4.1)	.383		

Risk factor	Univariable		Cox proportional hazard	
	HR (95% CI)	*P* value	HR (95% CI)	*P* value
Overall mortality				
AA obstruction	1.7 (0.8-3.3)	.142		
Coronary anomaly	2.7 (1.3-5.4)	.005	2.4 (1.2-4.9)	.013
DiGeorge syndrome	1.1 (0.5-2.1)	.870		
Neonate	2.4 (1.3-4.1)	.002		
Low weight (<2.5 kg)	3.9 (1.8-8.3)	<.001	3.5 (1.6-7.6)	.001
TV surgery	1.3 (0.6-2.8)	.468		
Early reoperation	1.7 (0.9-3.4)	.103		

OR, Odds ratio; *CI*, confidence interval; *TVI*, truncal valve insufficiency; *AA*, aortic arch; *ICU*, intensive care unit; *TV*, truncal valve; *HR*, hazard ratio.

Mortality

Early mortality was 13.3% (34 of 255). Over the last 20 years, the median age at surgery decreased from 70.5 days (range, 1 day to 8.7 years) between 1979 and 1998 to 26 days (range, 2 days to 3.1 years) between 1999 and 2018 ($P < .001$). Early mortality was 11.9% (15 of 126) between 1979 and 1998 and 14.7% (19 of 129) between 1999 and 2018 ($P = .507$). Risk factors for early mortality are summarized in Table 2. There was no significant difference in early mortality between centers (18% [12 of 67] in Brisbane vs 12% [22 of 188] in Melbourne; $P = .199$).

There were 23 late deaths (10.4%; 23 of 221), and overall survival was 76.8 ± 2.9% (95% confidence interval [CI], 70.4%-81.9%) at 20 years. Most deaths (82.5%; 47 of 57) occurred within the first year following repair. If a patient survived to 1 year, survival thereafter was excellent, with Kaplan–Meier survival of 93.5 ± 2.2% (95% CI, 87.6%- 96.7%) at 20 years (Figure 1). Causes of death are presented in Table 3. Late mortality was not impacted by era of surgery, with 13 late deaths during 1979 to 1998 and 10 late deaths during 1999 to 2018 ($P = .524$). Risk factors for late death are summarized in Table 2.

Neonatal Surgery

Ninety-three neonates underwent TA repair. The proportion of neonates increased over time, from 19% (24 of 126 total; 23 of 110 in Melbourne; 1 of 16 in Brisbane) between 1979 and 1998 to 53% (68 of 128 total; 40 of 77 in Melbourne; 28 of 51 in Brisbane) between 1999 and 2018 ($P < .001$). There were no significant differences in neonatal volume between centers over time ($P = .163$ between 1979 and 1988; $P = .74$ between 1999 and 2018). The median age of neonates was 13 days (range, 1-28 days), and that of older patients was 70.5 days (range, 30 days to 8.7 years). Early mortality in neonates was 23.7% (22 of 93) in neonates, compared with 7.4% (12 of 162) in older patients ($P < .001$). Neonatal surgery was a risk factor for early mortality on multivariable analysis (odds ratio [OR], 2.9; 95% CI, 1.3-6.8; $P = .012$). Although the proportion of neonates increased over the study period (Figure 2, *A*), the proportion of neonatal early deaths did not change significantly over time (25% [6 of 24] between 1979 and 1998 vs 23% [16 of 69] between 1999 and 2018; $P = .322$). Overall survival at 20 years was 68.9 ± 4.9% (95% CI, 58.2%-77.4%) in neonates and 82.2 ± 3.4% (95% CI, 74.4%-87.8%) in older patients ($P = .002$) (Figure 2, *B*).

The rate of total deaths within 1 year was 38% (9 of 24) in neonates who underwent TA repair in week 1, 21% (6 of 29) in those who did so in week 2, 19% (5 of 27) in those who did so in week 3, and 46% (6 of 13) in those who did so in week 4 (Figure 3, *A*). The highest proportion of total deaths within 1 year occurred in neonates who underwent TA repair in weeks 1 and 4, although the differences did not reach statistical significance. The 10-year survival was 60.9 ± 10.2% (95% CI, 38.3%-77.4%) in neonates who underwent surgery in the first week of life (n = 24), 71.8 ± 8.5% (95% CI, 51.5%-84.8%) in those who did so in the second week of

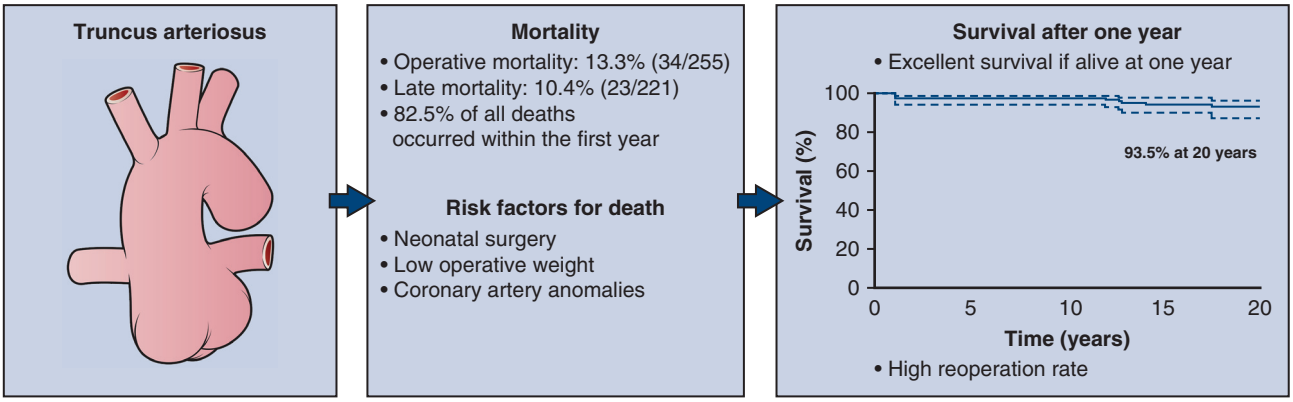

FIGURE 1. Risk factors and outcomes following truncus arteriosus repair.

life (n = 29), 81.3 ± 7.5% (95% CI, 60.8%-91.8%) in the third week of life (n = 27), and 53.9 ± 13.8% (95% CI, 24.8%-76.0%) in those who did so in the fourth week of life (n = 13) (Figure 3, *B*). Neonates who underwent surgery in the first week ($P = .007$, log-rank test), and fourth week ($P = .002$, log-rank test) had worse survival compared with those who did so in weeks 2 and 3.

Neonates had a higher proportion of significant comorbidities (ie, significant concomitant anomalies [eg, moderate or greater truncal valve insufficiency, interrupted aortic arch, coronary artery anomaly, low operative weight] and/or necessitating preoperative intensive care) compared with older patients (78% [73 of 93] vs 39% [63 of 162]; $P < .001$). Within the neonatal group, significant comorbidities were present in 96% (23 of 24) who underwent TA repair in the first week of life, 76% (22 of 29) of those who did so in the second week, 67% (18 of 27) of those who did so in the third week, and 77% (10 of 13) of those who did so in the fourth week. Neonates who underwent surgery in the first week had a higher proportion of significant comorbidities compared with those who did so in weeks 2 to 4 combined (96% [23 of 24] vs 72% [50 of 69]; $P = .019$). When including only patients with significant concomitant anomalies (ie, excluding those who solely required intensive care and did not have concomitant anomalies), significant concomitant anomalies were present in 92% (22 of 24) of neonates who underwent surgery in the first week, 62% (18 of 29) of those who did so in the second week, 41% (11 of 27) of those who did so in the third week, and 31% (4 of 13) of those who did so in the fourth week. Neonates who required TA repair in the first week of life had a higher proportion of significant concomitant anomalies compared with those who required repair in weeks 2, 3, and 4 ($P < .001$ for all). Furthermore, the rate of ICU admission solely for management of heart failure was highest in neonates who underwent TA repair in week 4 (46%; 6 of 13), which was statistically significantly different compared with those who did so in week 1 (4%; 1 of 24; $P = .004$) and week 2 (14%; 4 of 29; $P = .045$) but not compared with those who did so in week 3 (26%; 7 of 27; $P = .28$). In addition, neonates who underwent TA repair in week 4 appeared to have more ICU admissions for the management of heart failure than in the subsequent 8 weeks of life (46% [6 of 13] vs 20% [19 of 93]; $P = .074$).

TABLE 3. Causes of death following truncus arteriosus repair

Cause of death	% (n/N)
Early death	13.3 (34/255)
Cardiac failure	4.7 (12/255)
Myocardial ischemia	1.6 (4/255)
Respiratory failure	1.6 (4/255)
Sepsis	1.2 (3/255)
Sudden cardiac arrest	1.2 (3/255)
Unable to wean from cardiopulmonary bypass	1.2 (3/255)
Unknown	0.8 (2/255)
Brain hemorrhage and respiratory failure	0.4 (1/255)
Exsanguination from conduit	0.4 (1/255)
Seizure disorder	0.4 (1/255)
Within 1 y	6.3 (14/221)
Unknown	2.3 (5/221)
Respiratory failure	1.4 (3/221)
Respiratory tract infection	0.9 (2/221)
Cardiac failure	0.5 (1/221)
Progressive pulmonary hypertension	0.5 (1/221)
Sudden cardiac arrest	0.5 (1/221)
Unknown infection	0.5 (1/221)
After 1 y	4.8 (10/208)
Acute respiratory failure secondary to infection	1.4 (3/221)
Unknown	0.9 (2/221)
Candida sepsis with T cell lymphoma	0.5 (1/221)
Cardiac failure	0.5 (1/221)
Sudden cardiac arrest	0.5 (1/221)
Thromboembolism following catheterization	0.5 (1/221)

Coronary Artery Anomalies

Twenty-seven patients had a coronary artery anomaly. The most common coronary artery anomaly was a single

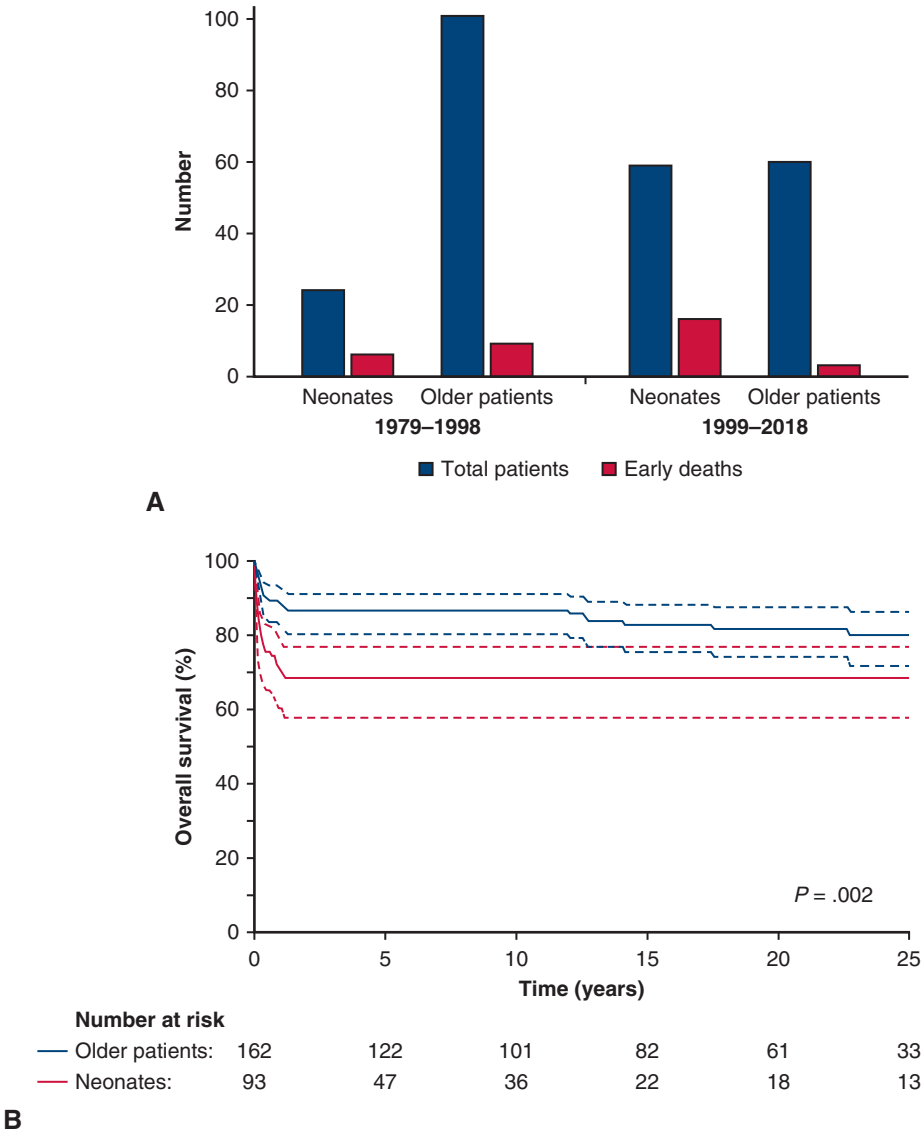

FIGURE 2. Early mortality over time and Kaplan–Meier overall survival of neonates and non-neonates following truncus arteriosus repair. A, Proportions of neonates and older patients (*blue*) and associated early mortality (*red*) by era. B, Kaplan–Meier overall survival in neonates (*red*) vs nonneonates (*blue*). *Solid lines* represent overall survival; *dashed lines*, 95% confidence interval. *P* values are from log-rank tests.

coronary artery, in 14 patients (single left coronary artery, n = 8; single right coronary artery, n = 6), of whom 7 had a major branch crossing the right ventricular outflow tract. Five patients had an intramural coronary artery, 3 had slit-like coronary ostia, and 2 had a coronary artery arising from the pulmonary artery. Of the 27 coronary artery anomalies, only 12 were noted on preoperative echocardiography. Five patients underwent repair of their anomalous coronary artery, which included unroofing of an intramural coronary artery in 4 patients and reimplantation of a coronary artery from the pulmonary artery in 1 patient. Three patients required early reoperation for unroofing of an anomalous coronary artery. In patients with a coronary artery anomaly, there were 6 early deaths (22.2% 6 of 27) and 4 late deaths (19.0%; 4 of 21). Overall survival was 39.6 ± 15.6% (95% CI, 11.8%-66.9%) at 20 years in patients with a coronary artery anomaly, compared with 78.4 ± 3.1% (95% CI, 71.6%-83.8%) at 20 years in patients without a coronary artery anomaly ($P = .004$) (Figure 4). Four of the 10 patients who died (40%) had a major coronary artery branch crossing the right ventricular outflow tract. The coronary artery anomaly was identified as a risk factor for late mortality on Cox regression (hazard ratio [HR], 3.7; 95% CI, 1.2-11.2; $P = .019$). Fourteen neonates had a coronary artery anomaly, with 4 deaths (all early).

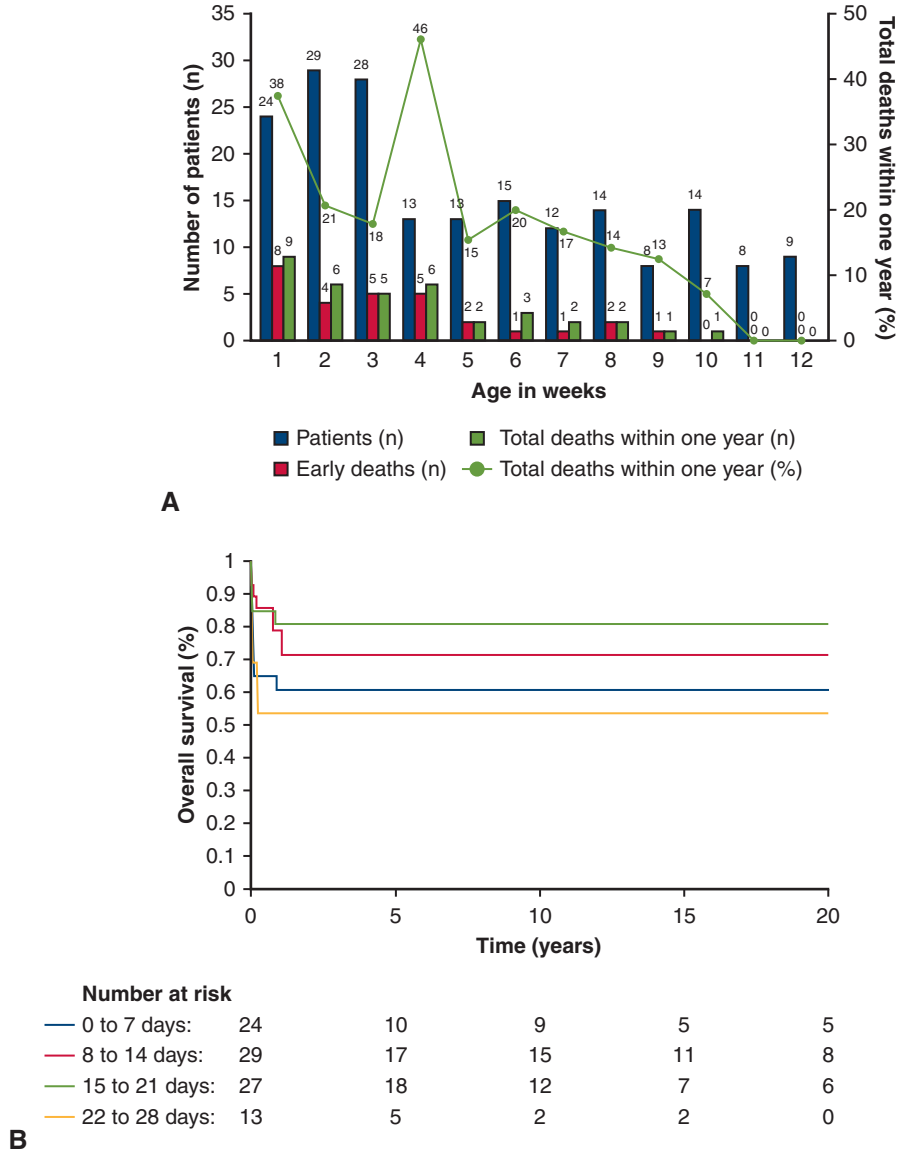

FIGURE 3. Survival following truncus arteriosus (TA) repair by week of repair. A, Age in weeks at the time of TA repair (total patients, *blue*), with the number of early deaths (*red*) and 1-year deaths (*yellow*) on the primary axis and the percentage of 1-year deaths (*yellow line*) on the secondary axis. B, Kaplan–Meier overall survival of neonates by week of TA repair. Mean 10-year survival was 60.9 ± 10.2% (95% CI, 38.3%-77.4%) in neonates age 0 to 7 days (*blue*), 71.8 ± 8.5% (95% CI, 51.5%-84.8%) in neonates age 8 to 14 days (*red*), 81.3 ± 7.5% (95% CI, 60.8%-91.8%) in neonates age 15 to 21 days (*green*), and 53.9 ± 13.8% (95% CI, 24.8%-76.0%) in neonates aged 22 to 28 days (*yellow*).

Reoperation

A total of 175 patients required at least 1 reoperation (Table 3), with overall freedom of reoperation of 2.9 ± 1.5% (95% CI, 0.9-7.1) at 20 years. Thirty-four patients (13.3%) required early reoperation. Reoperative procedures are summarized in Table 4. Risk factors for reoperation are summarized in Table 5. Neonatal surgery was a risk factor for early reoperation on multivariable analysis (OR, 4.2; 95% CI, 1.9-9.1; $P < .001$). Freedom from any reoperation in neonates was 39.9 ± 6.2% at 5 years and 21.2 ± 6.0% at 10 years, compared with 50.8 ± 4.4% at 5 years and 22.2 ± 3.8% at 10 years in older patients. There was no significant difference in freedom from reoperation between neonates and older patients ($P = .087$).

During the follow-up period, 45 patients had a percutaneous transcatheter reintervention, including pulmonary artery dilation in 36 patients, Melody (Medtronic, Minneapolis, Minn) pulmonary valve insertion in 4 patients, aortic arch dilation in 2 patients, coiling of major aorticopulmonary collateral arteries in 1 patient, patent foramen ovale closure in 1 patient, and superior vena cava dilation in 1 patient.

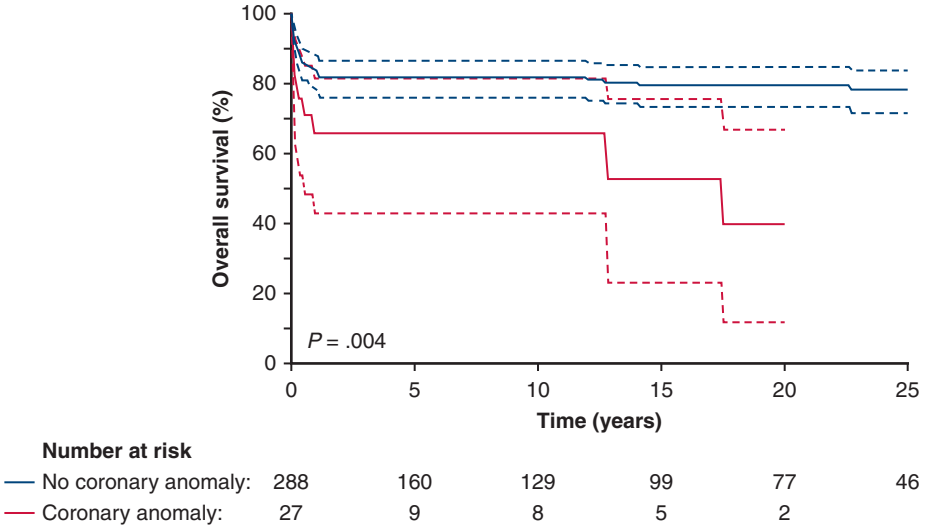

FIGURE 4. Kaplan–Meier overall survival of patients with (*red*) and without (*blue*) a coronary artery anomaly. Coronary artery anomalies include a single coronary artery, major coronary artery crossing the right ventricular outflow tract, intramural coronary artery, slit-like coronary ostia, or a coronary artery arising from the pulmonary artery. The *solid line* represents overall survival; *dashed lines*, the 95% confidence interval. *P* values are from the log-rank test.

Right Ventricular Outflow Tract

Continuity between the right ventricle and pulmonary artery was established using a conduit in 239 patients and direct right ventricle–to–pulmonary artery anastomosis in 16 patients. The median conduit size was 12 mm (mean 12.3 mm; range, 5-20 mm).

A total of 231 right ventricular outflow tract reoperations were performed in 159 patients. Sixty-four patients had at least 2 conduit replacements, and 8 had 3 conduit replacements. The median time to right ventricular outflow tract reoperation was 4.3 years (range, 7 days to 18.3 years). Overall, freedom from right ventricular outflow tract reoperation was 25.4 ± 3.4% (95% CI, 19.0%-32.3%) at 10 years and 3.4 ± 1.8% (95% CI, 3.1%-11.8%) at 20 years. Freedom from right ventricular outflow tract reoperation was 54.2 ± 6.6% at 5 years and 28.5 ± 6.7% at 10 years in neonates, compared with 55.5 ± 4.4% at 5 years and 23.7 ± 3.9% at 10 years in older patients. There was no significant difference in freedom from right ventricular outflow tract reoperation between neonates and older patients ($P = .98$, log-rank test). There was no early mortality following right ventricular outflow tract reoperation. Seven patients who underwent direct right ventricle–to– pulmonary artery anastomosis required reoperation with conduit placement at a median time of 1.4 years (range, 8 days to 8.8 years). Freedom from right ventricular outflow tract reoperation in patients who underwent direct anastomosis was 35.2 ± 15.4% (95% CI, 9.3%-63.3%) at 10 years ($P = .274$, compared with patients who underwent conduit repair).

Truncal Valve

The truncal valve anatomy is summarized in Table 1. Overall survival at 20 years was 79.5 ± 3.7% (95% CI, 71.2%-85.7%) in patients with no truncal valve insufficiency, 76.8 ± 5.4% (95% CI, 64.1%-85.6%) in those with mild insufficiency, 76.9 ± 8.3% (95% CI, 55.4%-88.9%) in those with moderate insufficiency, and 22.2 ± 19.3% (95% CI, 1.0%-61.5%) at 10 years in those with severe insufficiency. The degree of truncal valve insufficiency was not associated with mortality (Table 2).

Concomitant truncal valve surgery was performed in 33 patients (truncal valve repair, n = 31; truncal valve replacement, n = 2), including 20 neonates. These patients included 3 with no insufficiency, 7 with mild insufficiency, 17 with moderate insufficiency, and 6 with severe insufficiency. Of the 3 patients with no truncal insufficiency on initial preoperative transthoracic echocardiogram, 2 had moderate to severe truncal valve stenosis that was addressed at the time of truncus repair, and 1 required resuspension of truncal commissures to facilitate unroofing of an intramural coronary artery. Of the 7 patients with mild insufficiency on the initial preoperative transthoracic echocardiogram, 4 were deemed to have at least moderate insufficiency on subsequent imaging, 2 had large myxoid nodules on the valve leaflets that were deemed problematic, and 1 had moderate truncal valve stenosis. Overall survival at 20 years was 74.3 ± 7.9% (95% CI, 55.0%-86.2%) in patients who underwent concomitant truncal valve surgery, compared with 77.4 ± 3.1% (95% CI, 70.6%-82.8%) in those who did not.

TABLE 4. Reoperative procedures

Reoperative procedure	Number*
Early reoperations	
Right ventricular outflow tract reconstruction	12
Residual ventricular septal defect closure	4
Aortic arch reconstruction	3
Branch pulmonary artery reconstruction	3
Coronary artery unroofing	3
Truncal valve replacement	3
Bidirectional cavopulmonary shunt	2
Interposition graft to aorta to relieve bronchial obstruction	2
Laparotomy	2
Aortic root repair	1
Pulmonary embolectomy	1
Replacement of superior vena cava and innominate vein due to obstruction	1
Vascular ring division	1
All reoperations	
Right ventricular outflow tract reconstruction	159
Pulmonary artery branch reconstruction	48
Truncal valve reoperation	36
Truncal valve repair	19
Truncal valve replacement	17
Right ventricular outflow tract myectomy	10
Residual ventricular septal defect closure	6
Aortic arch reconstruction	6
Left ventricular outflow tract repair	5
Aortic root repair	3
Coronary artery unroofing	4
Laparotomy	3
Bidirectional cavopulmonary shunt	2
Atrial septal defect closure	1
Cardiac transplantation	1
Excision of supramitral ring	1
Partial anomalous pulmonary venous connection repair	1
Pulmonary embolectomy	1
Replacement of superior vena cava and innominate vein due to obstruction	1
Tricuspid annuloplasty	1
Vascular ring division	1

*Some patients may have undergone a combination of the procedures listed.

Overall freedom from late truncal valve surgery (including truncal valve reoperation) was 79.3 ± 3.3% (95% CI, 71.9%-85.0%) at 20 years. Concomitant truncal valve surgery was identified as a risk factor for late truncal valve surgery (HR, 6.5; 95% CI, 3.1%-13.3%; $P < .001$). Sixteen patients underwent truncal valve reoperation at a median time of 2.6 years (mean, 3.8 years; range, 1 day to 17.8 years). Freedom from truncal valve reoperation was 27.5 ± 11.2% (95% CI, 9.0%-49.9%) at 20 years. Of the 222 patients who did not require concomitant truncal valve surgery, 20 required late truncal valve surgery, and freedom from late truncal valve surgery was 86.3 ± 3.0% (95% CI, 79.1%-91.2%) at 20 years. Of these 20 patients, 9 had a quadricuspid truncal valve, including 6 with initially mild insufficiency and 3 with moderate insufficiency. Freedom from late truncal valve surgery at 20 years was 73.9 ± 7.8% (95% CI, 55.1%-85.8%) in patients with a quadricuspid truncal valve, compared with 90.3 ± 3.0% (95% CI, 82.3%-94.8%) in those without a quadricuspid valve ($P = .023$) (Figure 5). At last follow-up, 89.5% (171 of 191) of the patients had no or mild insufficiency, and 6.3% (12 of 191) had moderate or severe insufficiency. Follow-up truncal valve data were unavailable in 8 patients. No patients experienced aortic dissection or aortic rupture during the study period; however, 2 patients had a dilated truncal root necessitating repair.

Follow-up Status

Follow-up of survivors was 96% complete (191 of 198). Seven patients were lost to follow-up. The median duration of follow-up was 16.4 years (mean, 17.0 years; range, 6 months to 38.1 years). At last follow-up, 190 patients were in New York Heart Association class I/II and 1 patient was in class III. Right ventricular function was normal in 59.7% (114 of 191), mildly reduced in 12.0% (23 of 191), and moderately reduced in 1.6% (3 of 191).

DISCUSSION

In our experience of TA repair spanning 4 decades, there was no impact of era on rates of mortality or reoperation. Neonatal surgery was identified as risk factor for early mortality, with a neonatal mortality of 23.7%, compared with 7.4% in older patients. Ninety-three neonates underwent TA repair, and although the proportion of neonates undergoing this operation increased over the study period, their early mortality remained unchanged. Surgery has become a common practice in neonates with TA; however, neonatal surgery is not without its challenges, particularly in patients with complex concomitant cardiac anomalies. Among the 22 neonates in our cohort who died early, 6 had moderate or severe truncal insufficiency (2 patients <2.5 kg), 6 had aortic arch obstruction (2 patients <2.5 kg), and 4 had a coronary artery anomaly. Interestingly, when analyzing neonates based on their week of operation, we found significantly worse survival in that neonates undergoing TA repair in the first or fourth week of life than in those operated on in week 2 or 3. Neonates in the first week tended to present in a more critical state, often requiring admission to the ICU for support, or had significant concomitant anomalies, including moderate to severe truncal valve insufficiency, aortic arch obstruction, coronary artery anomalies, or low weight. In fact, 92% (all but 2 of the 24 neonates) who underwent TA repair in the first week of life had a significant concomitant anomaly, compared with 62% (18 of 29) who did so in the second week, 41% (11 of 27) who did so in the third week, and 31% (4 of 13) who did so in the fourth week. This is an interesting finding, given that in isolation, these concomitant anomalies were not

TABLE 5. Risk factors for reoperation

Risk factor	Univariable OR (95% CI)	Univariable *P* value	Multivariable regression OR (95% CI)	Multivariable regression *P* value
Early reoperation				
Severe TVI	6.9 (1.3-35.9)	.021	4.1 (0.7-22.6)	.105
AA obstruction	2.1 (0.9-5.1)	.096		
Neonate	4.5 (2.1-9.8)	<.001	4.2 (1.9-9.1)	<.001
Preoperative ICU admission	1.1 (0.5-2.4)	.810		
TV surgery	0.9 (0.3-2.7)	.826		

Risk factor	Univariable HR (95% CI)	Univariable *P* value	Cox proportional hazard HR (95% CI)	Cox proportional hazard *P* value
Right ventricular outflow tract reoperation				
Neonate	1.0 (0.7-1.4)	.906		
DiGeorge syndrome	1.5 (1.0-2.2)	.067	1.9 (1.2-2.8)	.005
Direct anastomosis	0.7 (0.3-1.4)	.277		
Hancock conduit	1.9 (1.4-2.8)	<.001	2.3 (1.6-3.4)	<.001
Conduit size	0.9 (0.9-1.0)	.044	0.9 (0.9-1.0)	.006
Truncal valve reoperation				
Tricuspid TV	0.3 (0.1-0.6)	<.001		
Quadricuspid TV	3.4 (1.7-6.5)	<.001		
Quadricuspid TV and > moderate TVI	10.4 (5.0-21.4)	<.001	2.4 (0.9-6.8)	.088
No TVR	0.2 (0.1-0.4)	<.001	0.3 (0.1-0.7)	.009
Moderate TVI	9.9 (4.5-20.3)	<.001		
Severe TVI	33.9 (9.0-127.9)	<.001		
Neonate	2.5 (1.3-4.9)	.007		
TV surgery	8.5 (4.3-16.8)	<.001	2.9 (1.1-7.7)	.037

OR, Odds ratio; *CI*, confidence interval; *TVI*, truncal valve insufficiency; *AA*, aortic arch; *ICU*, intensive care unit; *TV*, truncal valve; *HR*, hazard ratio; *TVR*, truncal valve repair.

identified as risk factors for mortality, but when combined in the neonatal subgroup of patients, neonatal surgery per se became a risk factor for mortality. Thus, neonatal surgery may be a surrogate risk factor for these previously reported higher-risk patients. Clearly, neonates emergently requiring surgery in the first days of life are in a more critical state that puts them at greater risk of a poor outcome. Furthermore, neonates who underwent repair during the fourth week of life had the highest proportion of patients who required admission to the ICU solely for the management of heart failure and did not have any significant concomitant anomalies. This suggests that those neonates who were operated

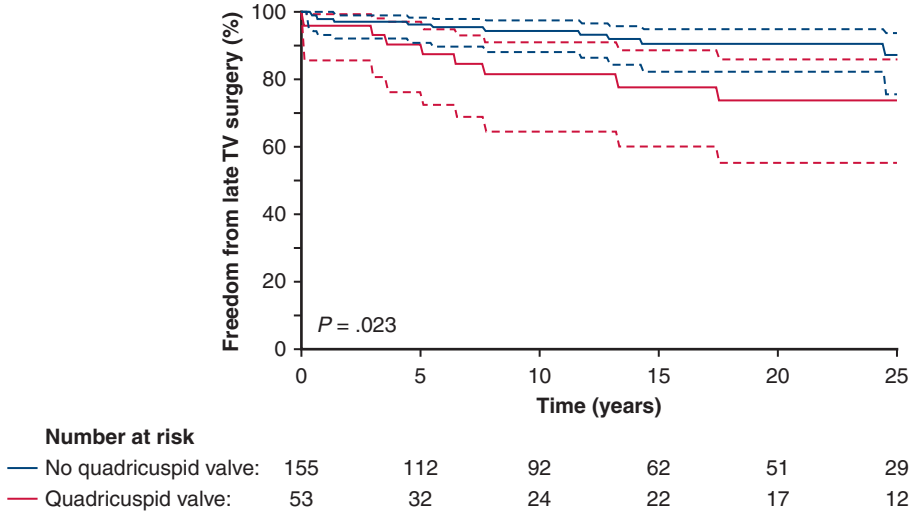

FIGURE 5. Freedom from late truncal valve surgery of patients with and without a quadricuspid truncal valve. *Solid lines* represent freedom from truncal valve surgery; *dashed lines*, 95% confidence interval. *P* values are from the log-rank test. *TV*, Truncal valve.

on in week 4 had overcirculation and worsening heart failure over time. The neonates operated on during the fourth week of life had the highest mortality during the first year of life (Figure 3, *B*). Importantly, there also appeared to be fewer admissions to the ICU solely for the management of heart failure beyond the fourth week. Although the number of admissions to the ICU solely for heart failure management in weeks 3 and 4 did not reach statistical significance, likely due to the relatively small number of patients, almost twice as many neonates were admitted to the ICU for heart failure management in week 4 compared with week 3. Collectively, this indicates that any neonate with signs of overcirculation should be operated on as soon as possible. Those who survive beyond the neonatal period and present late in their clinical course might have been "naturally selected" to survive (in some cases for up to 8 years).

Most deaths (14 of 23 late deaths) in our cohort occurred within the first year after TA, similar to the findings of previous studies.[11,14,16-20] Rajasinghe and colleagues[18] reported that 57% (13/23) of their late deaths occurred within the first year after repair. Similarly, Tlaskal and colleagues[11] reported that 88% (7 of 8) of late deaths occurred within the first year. Given this, patients with TA should have more intensive follow-up within the first year after repair. Survival beyond the first year is associated with excellent outcomes.

Of the 10 deaths in patients with a coronary artery anomaly, 4 occurred in patients with a major branch coronary artery crossing the right ventricular outflow tract, which may have resulted from compression of the coronary artery. Although the reasons for these deaths cannot be definitively determined, compression of the branch coronary artery by the overlying conduit may be a factor. Coronary artery anomalies have been reported as risk factors for mortality.[4,5,14,21-24] In a cohort of 13 patients, Schreiber and colleagues[24] concluded that the presence of a coronary artery anomaly was associated with poorer surgical outcome, related to compression or distortion of the anomalous coronary artery. Although coronary artery anomalies have been reported in 5% to 20% of patients with TA, it is difficult to ascertain the precise incidence of this anomaly. In patients with TA, it is not uncommon for a coronary artery anomaly to be missed on preoperative echocardiography; in fact, only 12 of the 27 patients in our present cohort with a coronary artery anomaly were identified by preoperative echocardiography, with the remaining coronary artery anomalies discovered intraoperatively. Thus, without clear delineation of both the coronary ostia and the epicardial course, many of these anomalies may be missed entirely. Given the importance of the coronary arteries, it is imperative that the coronary anatomy be clearly noted both with respect to its origin and epicardial course, as a major branch crossing the right ventricular outflow tract may become compromised on right ventriculotomy, compressed by an overlying conduit, or distorted by a large truncal root.[21,22]

Truncal valve insufficiency was present in 43.9% of the patients in our cohort. Mild insufficiency is often well tolerated and not associated with mortality, whereas moderate or severe insufficiency has been reported to be a risk factor for death.[6,11,13,25-27] Neither the degree of insufficiency nor concomitant truncal valve surgery was identified as a risk factor for death in our cohort. Russell and colleagues[28] reported on 23 truncal valve operations in 572 patients between 2000 and 2009 and concluded that failure to address significant truncal valve insufficiency was associated with poor outcomes. Our cohort included 30 patients with moderate insufficiency and 6 with severe insufficiency, 33 of whom underwent concomitant truncal valve surgery. All 6 patients with severe insufficiency underwent concomitant truncal valve surgery, with 4 deaths (2 early, 2 late) and 4 truncal valve reoperations, at a median of 50 days. Of the patients with moderate insufficiency, 17 underwent concomitant truncal valve surgery, with 2 deaths (early) and 8 truncal valve reoperations at a median of 2.6 years. In the remaining 13 patients with moderate insufficiency who did not undergo concomitant truncal valve surgery, 5 required late truncal valve surgery and 5 died before any intervention; at the time of this report, only 3 patients with initial moderate insufficiency were alive without any intervention. Therefore, we recommend that patients with moderate or greater insufficiency undergo truncal valve surgery at the time of TA repair. Although the durability of repair remains questionable, it is preferable over replacement during the neonatal period, particularly if reduction of the annulus is performed and good repair is achieved.[29,30]

Despite the high (albeit expected) reoperation rate, the long-term outcomes of patients with TA are good for those who survive beyond 1 year after the initial surgery. Importantly, all but 1 patient in our cohort was in New York Heart Association class I/II. The fate of the truncal valve is good in patients with mild insufficiency, whereas those with moderate or greater insufficiency often required valve repair, particularly those with a quadricuspid truncal valve. We have previously reported a good quality of life in patients who underwent successful TA repair.[31]

This study is limited by its retrospective nature. Perioperative techniques varied over the course of the study period. Some outcome variables applied to a relatively small number of patients, limiting the multivariate analysis. Diagnosis of syndromes early in the study period was limited owing to a lack of definitive testing at the time. Coronary artery anomalies may be underrepresented as many are only noted on intraoperative reports.

CONCLUSIONS

TA repair in the neonatal period still presents significant surgical challenges. Neonates with signs of overcirculation

should be operated on promptly. The presence of a coronary artery anomaly is a risk factor for late death. Survival beyond the first year after repair is associated with excellent outcomes.

Conflict of Interest Statement

Dr d'Udekem reports personal fees from Actelion and Berlin Heart. All other authors report no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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