Original Article

Extracardiac Conduit versus Lateral Tunnel Fontan: Three Decades of Experience and Long-Term Patient Outcomes

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Abstract

Background: **The Fontan operation has undergone substantial evolution, with a global shift from the lateral tunnel (LT) technique to the extracardiac conduit (ECC) approach. However, long-term comparative outcomes between these techniques remain inconsistently reported.**

Objective: **To evaluate early and late outcomes of patients who underwent Fontan completion over a 33-year period, comparing ECC and LT techniques.**

Methods: **A retrospective cohort study including 238 consecutive patients who underwent Fontan completion at a single tertiary cardiovascular center between 1990 and 2022. Early and late mortality, postoperative complications, and long-term survival (Kaplan–Meier analysis) were assessed.**

Results: **ECC was used in 81.9% of cases and LT in 16.8%. Early mortality was significantly higher in the LT group compared with ECC (35% vs. 12.3%; p = 0.001). Late mortality remained low and similar between groups. Overall mortality was 16.4% for ECC and 40% for LT. Long-term survival estimates consistently favored ECC at all evaluated time points (p < 0.001). Late complications – including heart failure and arrhythmias – were infrequent and showed no significant differences between techniques.**

Conclusion: **Over three decades, outcomes following the Fontan procedure have improved considerably. ECC was associated with superior long-term survival compared with LT, while early morbidity and late complication rates were comparable between groups.**

Keywords: **Fontan Procedure; Congenital Heart Defects; Treatment Outcome; Survival Rate.**

Introduction

The Fontan operation, first performed in 1971, has undergone substantial refinement since its initial description for tricuspid atresia. Early experience with the atriopulmonary connection revealed important limitations, including progressive atrial dilation, arrhythmias, and impaired long-term hemodynamics, prompting the development of more efficient cavopulmonary pathways.[1,2]

The introduction of the total cavopulmonary connection, either through a lateral tunnel (LT) or an extracardiac conduit (ECC), represented a major advance in Fontan physiology by reducing atrial manipulation and optimizing venous flow dynamics.[2-5] The LT technique, developed in the late 1980s, allowed growth potential within the intra-atrial baffle but maintained some degree of atrial exposure, which has been associated with an increased risk of atrial arrhythmias during long-term follow-up.[6-8] In contrast, the ECC approach minimizes atrial suturing and has been linked to smoother hemodynamics, a reduced arrhythmogenic substrate, and favorable intermediate outcomes in several series.[9-13]

Despite the widespread global adoption of ECC, evidence comparing ECC and LT remains heterogeneous. Variations in institutional practice, patient selection, surgical era, and staging strategies continue to influence outcomes across published studies.[5,12,14-16] Although improvements in perioperative care have reduced early mortality, long-term morbidity – including arrhythmias, thromboembolism, heart failure, protein-losing enteropathy, and Fontan-associated liver disease—continues to affect survival and functional status into adulthood.[16-20]

Few reports provide more than two to three decades of follow-up, and even fewer originate from centers with

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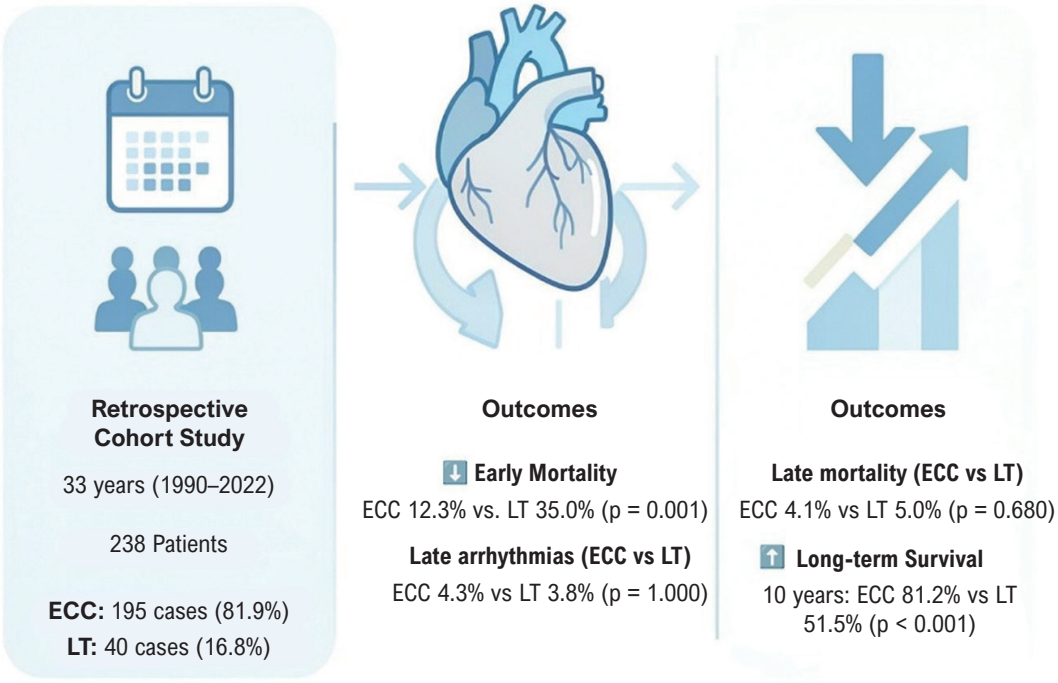
Central Illustration: Extracardiac Conduit versus Lateral Tunnel Fontan: Three Decades of Experience and Long-Term Patient Outcomes



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Fontan Operation: ECC vs. LT 33 Years of Experience. Graphical summary of a 33-year retrospective cohort study evaluating 238 patients who underwent Fontan completion. The illustration highlights the clinical transition and outcomes comparison between the Extracardiac Conduit (ECC) and Lateral Tunnel (LT) techniques, focusing on early mortality, postoperative arrhythmias, late mortality, and long-term survival estimates.

consistent surgical protocols over time.[5,20] Consequently, long-term comparison between ECC and LT remains clinically relevant, particularly in institutions that transitioned from LT to ECC during clearly defined operative periods.

In this context, the present study offers a comprehensive 33-year institutional experience with the Fontan procedure. The objective was to describe early and late outcomes in a large cohort of patients who underwent LT or ECC and to evaluate the impact of surgical technique and staging strategy on long-term survival and postoperative complications. The study design, population distribution, and main clinical outcomes are graphically summarized in the Central Illustration.

Methods

Study design and setting

This retrospective cohort study included all patients who underwent Fontan completion at a single tertiary cardiovascular center between January 1990 and December 2022. Clinical, operative, and follow-up data were obtained from institutional medical records.

Patient population

All consecutive patients who underwent Fontan completion during the study period were eligible for inclusion. Patients with active follow-up, postoperative

deaths, or incomplete long-term follow-up – but with complete hospitalization records – were retained. No exclusions were applied regarding anatomy, ventricular morphology, age at surgery, or staging strategy.

Data collection

Preoperative variables included congenital heart anatomy, ventricular function, ventricular dominance, the degree of atrioventricular valve regurgitation, and details of prior staged palliation. Stage I and II procedures were extracted from operative reports and encompassed Blalock-Taussig shunt placement, pulmonary artery banding, and the bidirectional Glenn procedure.

Intraoperative variables comprised age and weight at the time of Fontan completion, surgical technique (ECC or LT), use of fenestration, cardiopulmonary bypass and aortic cross-clamp durations, myocardial protection strategy, cardiac rhythm upon separation from bypass, and any concomitant atrioventricular valve surgery.

Postoperative data included duration of mechanical ventilation, vasoactive support requirements, incidence of prolonged ventilation (>24 hours), low cardiac output syndrome, acute kidney injury, postoperative bleeding, pleural effusion lasting >30 days, arrhythmias, and lengths of ICU stay and total hospitalization.

Follow-up variables included heart failure, arrhythmias, thrombotic events, protein-losing enteropathy, hepatic fibrosis, Fontan system failure, reinterventions, transplantation events, oxygen saturation, NYHA functional class, anticoagulation therapy, echocardiographic findings, causes of readmissions, and early and late mortality.

Surgical techniques

Lateral tunnel Fontan

The LT configuration follows the classical total cavopulmonary connection design, using an intra-atrial baffle to direct inferior vena cava flow toward the pulmonary arteries. This method was introduced to reduce atrial hypertension characteristic of the earlier atriopulmonary connection but still requires right atriotomy and substantial atrial manipulation.[1,6] Such manipulation has been associated with a greater propensity for atrial arrhythmias in long-term follow-up.[14]

Extracardiac conduit Fontan

The ECC technique connects the inferior vena cava to the pulmonary arteries using an external conduit, minimizing atrial incision and intra-atrial suture lines. This approach was developed to reduce arrhythmogenic substrate and promote smoother systemic venous flow, with several series reporting favorable intermediate and long-term hemodynamics.[5,9,11-13] All ECC procedures were performed under cardiopulmonary bypass, although aortic cross-clamping was not mandatory. A standardized 5-mm fenestration was created between conduit and right atrium when indicated.

Fenestration

Fenestration was used at the discretion of the operating surgeon and consisted of a 5-mm communication between the systemic venous pathway and the right atrium. This strategy has been widely adopted to modulate early postoperative hemodynamics and facilitate adaptation to the Fontan circulation.[3,21]

Outcome measures

The primary outcomes were all-cause mortality (early and late), time to first rehospitalization, Fontan system failure, and need for reintervention. Secondary outcomes included early postoperative complications, functional class, oxygen saturation, medication use, and echocardiographic findings.

Statistical analysis

Continuous variables were summarized as means and standard deviations when approximately normally distributed, and as medians with interquartile ranges when distributions deviated from normality, as indicated in the tables. Categorical variables were reported as absolute numbers and percentages. Comparisons between groups (ECC vs. LT and across operative periods or staging strategies) were performed using Student's t-test for normally distributed continuous variables and the Mann-Whitney U test for non-normally distributed variables; categorical variables were compared using chi-square or Fisher's exact tests, as appropriate. Overall survival after Fontan completion was estimated using Kaplan-Meier methods, and differences between ECC and LT were assessed with the log-rank (Mantel-Cox) test. To quantify the association between surgical technique and mortality, a Cox proportional hazards model with technique (LT vs. ECC) as the sole predictor was fitted, yielding hazard ratios with 95% confidence intervals. All analyses were conducted using Python, version 3.10.

Sex and gender information were obtained from electronic medical records. Clinical outcome analyses incorporated sex as a biological variable to identify potential differences in survival and complication rates between male and female patients, in accordance with the SAGER guidelines.

Generative artificial intelligence resources were used to support the style and readability review of this manuscript, while maintaining human editorial rigor and oversight, as stated at the end of the article.

Ethical considerations

The study adhered to the principles of the Declaration of Helsinki and to Brazilian regulations governing research involving human subjects. As a retrospective review, no identifiable patient information was used. All procedures complied with National Health Council guidelines and with the General Data Protection Law (LGPD). The research was approved by the institutional ethics committee under protocol number CAAE: 22574619.6.0000.5462.

Results

A total of 238 patients underwent Fontan completion, and their baseline characteristics are summarized in Table 1. The mean age at surgery was 7.4 ± 5.8 years, and 43.3% were

female. Tricuspid atresia was the most common diagnosis (41.2%), followed by double-outlet right ventricle (23.9%) and double-inlet left ventricle (16.0%). A predominant left ventricular morphology was present in 65.5% of patients. Regarding prior palliation, 13.0% underwent only Stage I, 27.3% only Stage II, 30.3% underwent both Stage I and II, and 29.4% underwent a primary Fontan. The ECC was the predominant Stage III configuration (81.9%), followed by the LT in 16.8%, while atriopulmonary connection was rarely used (1.3%). Fenestration was performed in 59.2% of procedures.

Temporal variation in surgical strategies across the four operative periods is shown in Table S1. ECC use increased steadily from 4% in Period I to 100% in Period IV, whereas LT declined from 84% to complete discontinuation. Primary Fontan became progressively less frequent, decreasing from 60% in Period I to 12% in Period IV. Fenestration use increased correspondingly, reaching 87% in Period IV.

Patient characteristics stratified by ECC and LT techniques are presented in Table S2. Patients who underwent ECC were older (7.8 ± 6.1 vs. 5.6 ± 3.6 years, p = 0.003) and heavier (23.2 ± 12.8 vs. 16.9 ± 7.6 kg, p < 0.001). Complete two-stage palliation was more frequent in the ECC group (34.4% vs. 12.5%, p = 0.002), whereas primary Fontan was more common among LT patients. Rates of fenestration, significant atrioventricular valve regurgitation, and valve surgery were similar between groups.

Operative times are detailed in Table 2. LT procedures required longer cardiopulmonary bypass times (110.0 vs. 90.0 minutes, p = 0.042) and substantially longer aortic cross-clamp times (80.0 vs. 0.0 minutes, p < 0.001). Mechanical ventilation duration, prolonged ventilation rates, ICU stay, and total hospitalization time were not significantly different between ECC and LT.

Early postoperative complications – defined as those occurring within 30 days – are summarized in Table 2. Shock occurred in approximately one-third of patients in both groups (33.1% ECC vs. 30.8% LT). Chylothorax was significantly more frequent among LT patients (15.4% vs. 3.7%, p = 0.033). Other early complications, including acute kidney injury, diaphragmatic paralysis, arrhythmias, pulmonary hypertensive crisis, pleural effusion, pneumonia, and stroke, showed no significant differences between techniques.

Mortality outcomes are presented in Table 3. Early mortality (≤ 30 days) was significantly higher in LT than ECC (35% vs. 12.3%, p = 0.001). Late mortality (> 30 days) remained low and similar across groups (5% vs. 4.1%, p = 0.680). Overall mortality was more than twice as high in LT compared with ECC (40% vs. 16.4%, p = 0.002). Long-term survival estimates are shown in Table 3, with ECC demonstrating significantly better survival at 30 days, 1 year, 5 years, and 10 years (all p < 0.001). The survival curves corresponding to these findings are depicted in Figure 1.

Mortality by operative period is displayed in Figure 2, which illustrates a clear temporal decline in early mortality – from 36% in Period I to 7.2% in Period IV – parallel to the transition from LT to ECC and the increased adoption of staged palliation.

Follow-up duration, differed significantly between groups. LT patients had longer follow-up (236.0 ± 87.3 months) than ECC patients (104.2 ± 79.8 months, p < 0.001), reflecting the earlier predominance of the LT technique.

Table 1 – Baseline characteristics of the study population

Variables	Mean ± SD or N (%)
Age (years)	7.4 ± 5.8
Female sex	103 (43.3%)
Weight at Fontan completion (Kg)	22.2 ± 12.3
Diagnosis	
– Tricuspid atresia	98 (41.2%)
– Atrioventricular septal defect	10 (4.2%)
– Double-inlet left ventricle	38 (16.0%)
– Double-outlet right ventricle	57 (23.9%)
– Hypoplastic single ventricle	6 (2.5%)
– Others	27 (11.3%)
Predominant ventricular morphology	
– Right	61 (25.6%)
– Left	156 (65.5%)
Type of Stage I procedure	
– Blalock–Taussig shunt	72 (30.3%)
– Pulmonary artery banding	43 (18.1%)
– Damus–Kaye procedure	4 (1.7%)
– Norwood–Sano	2 (0.8%)
– Others	3 (1.3%)
Type of Stage II procedure (n = 145)	
– Bidirectional Glenn (unilateral)	136 (93.7%)
– Damus–Kaye + Glenn	5 (3.4%)
– Norwood + Glenn	2 (1.4%)
– Others	2 (1.4%)
Staging prior to Fontan completion (n = 238)	
– Only Stage I	31 (13.0%)
– Only Stage II	65 (27.3%)
– Both Stage I and II	72 (30.3%)
– Primary Fontan	70 (29.4%)
Type of Stage III procedure (n = 238)	
– Extracardiac conduit	195 (81.9%)
– Lateral tunnel	40 (16.8%)
– Atriopulmonary connection	3 (1.3%)
Fenestration	141 (59.2%)
Moderate-to-severe AV valve regurgitation	15 (6.3%)
Concomitant AV valve surgery	11 (4.6%)

AV: atrioventricular.

Table 2 – Postoperative Outcomes and Complications

Variables	ECC (n = 163)	LT (n = 26)	p value
Cardiopulmonary bypass time (min)	90.0 [70.0; 110.0]	110.0 [100.0; 120.0]	0.042
Aortic cross-clamp time (min)	0.0 [0.0; 47.0]	80.0 [63.0; 87.0]	< 0.001
Mechanical ventilation time (hours)	12.0 [7.0; 25.0]	10.0 [7.0; 20.0]	0.308
Prolonged ventilation (≥ 24 h)	43 (26.7%)	9 (28.1%)	0.812
ICU stay (days)	5.0 [3.0; 7.0]	4.0 [3.0; 5.5]	0.501
Total hospitalization (days)	25.0 [18.0; 36.0]	23.5 [14.8; 45.5]	0.542
Complications			
Shock	54 (33.1%)	8 (30.8%)	0.812
Acute kidney injury	13 (8.0%)	2 (7.7%)	1.000
Diaphragmatic paralysis	12 (7.4%)	0 (0%)	0.377
Chylothorax	6 (3.7%)	4 (15.4%)	0.033
ICU arrhythmia	15 (9.2%)	4 (15.4%)	0.305
Pulmonary arterial hypertension crisis	9 (5.5%)	3 (11.5%)	0.218
Stroke	4 (2.5%)	1 (3.8%)	0.527
Pleural effusion	37 (22.7%)	8 (30.8%)	0.370

ECC: extracardiac conduit; LT: lateral tunnel; ICU: intensive care unit.

Table 3 – Mortality and Survival Analysis

Mortality	ECC (n = 195)	LT (n = 40)	p value
Early mortality	24 (12.3%)	14 (35%)	0.001
Late mortality	8 (4.1%)	2 (5%)	0.680
Overall mortality	32 (16.4%)	16 (40%)	0.002
Time	**ECC Survival (%)**	**LT Survival (%)**	**p value**
30 days	85.6%	57.6%	< 0.001
1 year	84.4%	54.5%	< 0.001
5 years	84.4%	51.5%	< 0.001
10 years	81.2%	51.5%	< 0.001

ECC: extracardiac conduit; LT: lateral tunnel

Late complications are summarized in Table S3. Heart failure was the most common late event (11% ECC vs. 7.7% LT), followed by arrhythmias (4.3% vs. 3.8%) and thrombotic events (4.3% vs. 3.8%). Protein-losing enteropathy occurred in 1.8% of ECC patients and in none of the LT patients. Hepatic fibrosis was rare, observed only in one LT patient. Rates of surgical reintervention were similar (15.7% ECC vs. 19.2% LT). None of the late complication rates differed significantly between the two techniques.

Discussion

This 33-year single-center experience provides a comprehensive evaluation of early and late outcomes following Fontan completion, with particular emphasis on the transition from the LT to the ECC technique. Several findings from our cohort align with contemporary international series, while others highlight the influence of surgical era, staged palliation, and institutional practice patterns on long-term results. Overall survival improved substantially over time,

and although ECC became the predominant configuration, late outcomes between techniques remained broadly comparable.

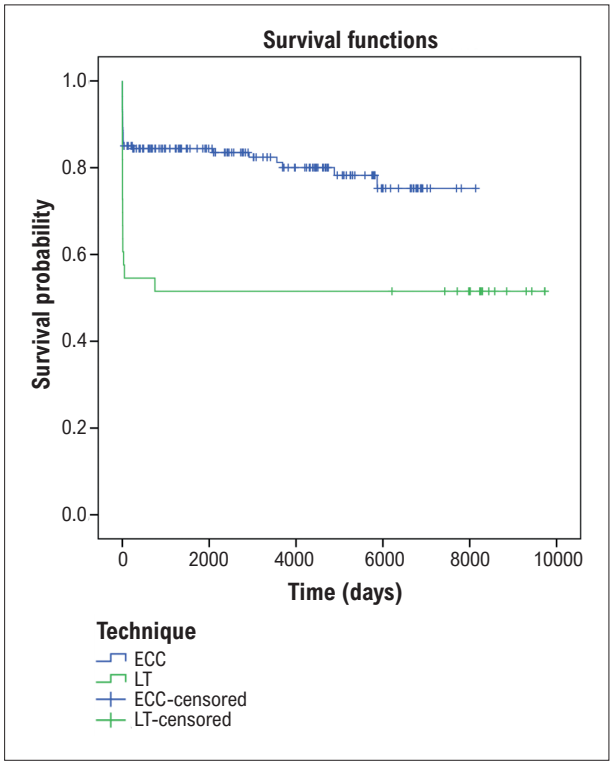

Figure 1 – *Kaplan–Meier survival curves by Fontan surgical technique (ECC versus LT). ECC: extracardiac conduit; LT: lateral tunnel*

In this cohort of 238 patients, ECC became the predominant technique in later decades following an institutional shift away from LT. Early mortality differed markedly between techniques, with significantly higher rates in LT (35%) compared with ECC (12.3%), according to consolidated results. Late mortality remained low in both groups, but the cumulative effect resulted in an overall mortality of 40% in LT and 16.4% in ECC. Survival consistently favored ECC at all evaluated time points, and despite differences in operative characteristics—particularly longer bypass and cross-clamp times with LT – late complications such as arrhythmias, thrombotic events, protein-losing enteropathy (PLE), and heart failure occurred at similarly low rates between groups. Most patients demonstrated preserved functional status at last follow-up, and rehospitalization and reintervention rates were modest and consistent with international experience.

Our findings mirror the global transition from atriopulmonary and LT configurations toward ECC, a trend also observed in international multicenter series.[9,10,12,13] The theoretical advantages of ECC – including reduced atrial manipulation, lower arrhythmogenic substrate, and improved flow dynamics – have been reinforced by reports demonstrating fewer late atrial arrhythmias and more stable hemodynamics compared with LT.[6,14] Although our early postoperative outcomes were similar between techniques, the substantial difference in early mortality and the higher cumulative mortality associated with LT are consistent with hazard ratios reported in other long-term follow-up studies.[5,14,16]

The relationship between staging strategy and outcomes identified in our series is also consistent with the literature. As demonstrated in our temporal analysis, the progressive reduction in primary Fontan procedures paralleled the decline in early mortality across successive periods. This pattern aligns with studies showing that staged palliation – particularly with a bidirectional Glenn – reduces perioperative risk and facilitates adaptation to

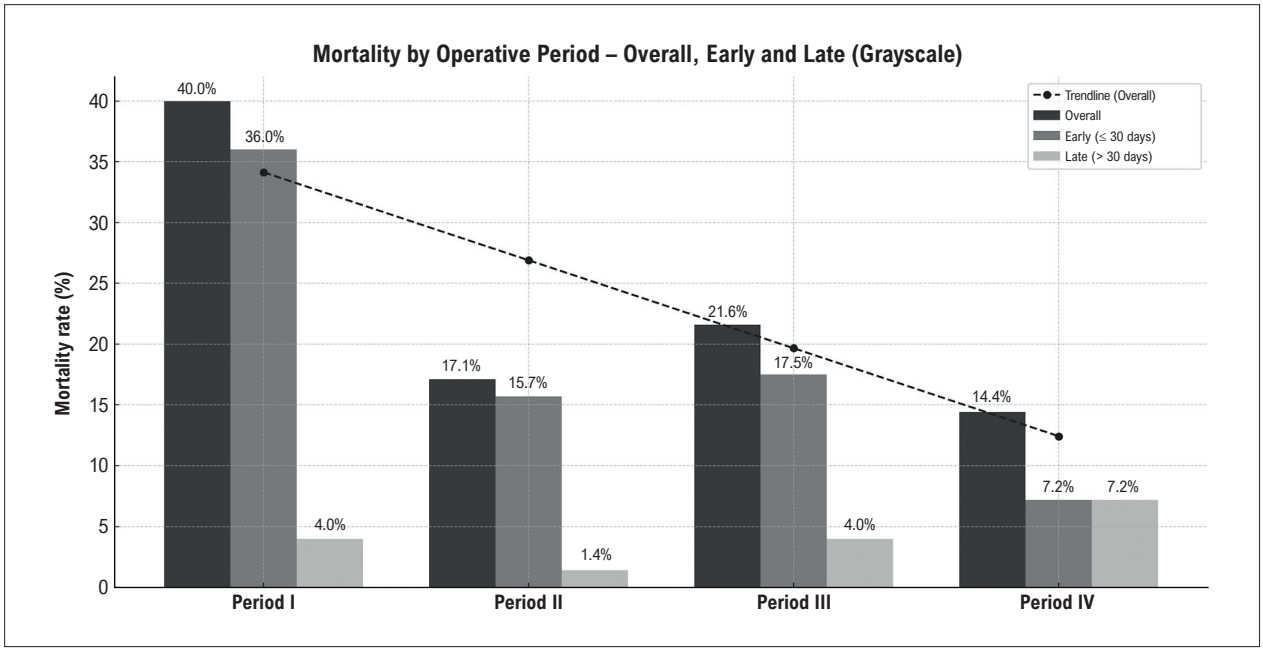

Figure 2 – *Mortality by Operative Period.*

Fontan physiology.[3,8,17,21] Similar observations have been reported in larger registries and multicenter analyses.[13,15]

Prolonged pleural effusion, postoperative arrhythmias, chylothorax, and low cardiac output remain among the most frequent early complications after Fontan completion, as widely documented.[7,10,11,14] In our cohort, the incidence of early events was consistent with published ranges, although the frequency of shock and pneumonia was somewhat higher. This likely reflects the earlier surgical eras represented in our dataset, during which perioperative protocols were less standardized. Comparable early complication rates between ECC and LT have been noted elsewhere,[5,14] supporting the interpretation that the survival advantage of ECC may be driven more by long-term hemodynamic and electrophysiological factors than by differences in immediate postoperative morbidity.

Long-term Fontan morbidity remains a persistent international challenge and includes arrhythmias, thromboembolic events, heart failure, PLE, and hepatic dysfunction.[18-20] In our study, late complications were relatively infrequent and consistent with reports from centers employing ECC predominantly in later eras.[9] The low incidence of arrhythmias aligns with the reduced atrial burden associated with ECC configurations.[6,14] The need for reinterventions – 15-20% in our cohort – is comparable to long-term follow-up studies reporting pacemaker implantation, conduit revision, or conversion procedures.[5,10,16]

Our mortality profile – characterized by a marked reduction in early deaths across operative periods – aligns with long-term survival curves from both U.S. and European series, where 20-30% mortality by 20–25 years is frequently reported.[12,14,15,17] The survival disadvantage associated with LT is consistent with established associations between atrial exposure, late atrial arrhythmias, systemic venous hypertension, and progressive Fontan failure.[2,6,7] Although ECC patients exhibited more rehospitalizations early in follow-up, this pattern likely reflects their concentration in more recent surgical eras with naturally shorter follow-up intervals.

The predominance of ECC in later periods appears to be driven by both hemodynamic and electrophysiological considerations. Reduced atrial manipulation and a streamlined cavopulmonary pathway likely contribute to the lower arrhythmia burden and improved long-term survival observed in ECC cohorts, a pattern mirrored in our results and multiple contemporary series.[9,13]

The strong association between staged palliation and improved outcomes underscores the physiological importance of pre-Fontan conditioning. Hemodynamic optimization prior to Fontan completion reduces volume load on the single ventricle and appears to support early postoperative stability, as demonstrated across decades of experience.[3,17,21]

Despite surgical refinements, Fontan physiology remains intrinsically vulnerable to progressive systemic venous congestion and diminished preload. The occurrence of late complications in our cohort – with rates similar to international experience – reinforces the chronic nature of Fontan circulation and the need for structured, lifelong surveillance.[16,18-20]

Regarding sex and gender equity, our cohort showed a balanced distribution of male and female patients (56.7% vs. 43.3%). Although some studies in congenital heart surgery suggest potential physiological differences in long-term Fontan hemodynamics between sexes, our analysis did not identify sex as an independent predictor of early or late mortality. These findings indicate that the benefits of the ECC over the LT technique are consistent across both sexes in our population.

A major strength of this study is its extensive 33-year follow-up, which captures the full evolution from LT to ECC and reflects real-world outcomes across multiple surgical eras. The large sample size, consistent operative techniques within each era, and comprehensive perioperative data enhance the reliability of the observed trends. Limitations include the retrospective design, potential unmeasured confounders, and the differential follow-up duration between groups – driven by the earlier predominance of LT – which may influence comparisons of late outcomes. Nonetheless, the overall findings are consistent with patterns described in major international reports.

This study reinforces the progressive improvement in outcomes associated with modern Fontan practice, particularly with the adoption of ECC and staged palliation. Despite persistent late morbidity, long-term survival remains favorable and comparable to international experience. Continued refinement of perioperative management and structured lifelong surveillance will remain essential as the global Fontan population ages.

Conclusion

In this 33-year experience with the Fontan procedure, outcomes improved substantially over time, reflecting the institutional transition from the lateral tunnel to the extracardiac conduit technique and the increased adoption of staged palliation. Although early morbidity remained notable, long-term survival was favorable and comparable to international series, with the extracardiac conduit demonstrating a survival advantage over the lateral tunnel. Late complications – including arrhythmias, thromboembolic events, protein-losing enteropathy, and heart failure – occurred at rates consistent with published experience, underscoring the chronic nature of Fontan physiology. These findings highlight the importance of surgical evolution, staged strategies, and structured lifelong follow-up to optimize outcomes in patients with single-ventricle congenital heart disease.

Author Contributions

Conception and design of the research: Saurith JAG, Jara AAD, Riso A, Guilhen JCS; Data collection: Mendonça FR, Moreira DG, Jara AAD, Silva FVA; Data analysis and interpretation: Saurith JAG, Guilhen JCS; Statistical analysis: Rösler AM; Manuscript drafting: Saurith JAG, Mendonça FR; Critical revision of the manuscript for important intellectual content: Saurith JAG, Ibanez OAP, Riso A, Pedra SF, Guilhen JCS.

Potential Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Sources of Funding

There were no external funding sources for this study.

Study Association

This study is not associated with any thesis or dissertation work.

Ethics approval and consent to participate

This study was approved by the Ethics Committee of the Instituto Dante Pazzanese de Cardiologia under CAAE 22574619.6.0000.5462. All the procedures in this study were in accordance with the 1975 Helsinki Declaration, updated in 2013.

Use of Artificial Intelligence

During preparation of this work, the authors used Gemini (Google) for language and formatting review. The authors reviewed and edited the content as needed and take full responsibility for the manuscript.

Data Availability Statement

The datasets generated and/or analyzed during this study are not publicly available due to institutional data protection policies and the sensitive nature of patient clinical records, but are available from the corresponding author upon reasonable request.

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*Supplemental Materials

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