



Anatomical Site and Patch Material as Determinants of Reintervention After Pulmonary Artery Patch Arterioplasty in Congenital Heart Disease: A Systematic Review

Stevano Mengko^{1*}, Timothy Agung Prabowo Mualim², Andrea Agitha Tarigan³, Adeline⁴

Samuel Moeda Naval Hospital, Indonesia¹

1st Marine Medical Battalion of the Indonesian Navy, Indonesia²

Indonesian Nav Doctrine, Education, and Training Command, Indonesia³

dr. Midiyato Suratani Naval Hospital, Indonesia⁴

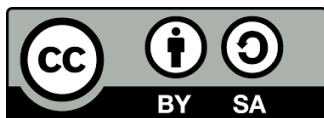
Email: stevano.mengko@gmail.com^{1*}, timothyagung94@gmail.com², tariganagitha@gmail.com³, adelin_saiwai@yahoo.com⁴

Keywords:

pulmonary artery; patch arterioplasty; congenital heart disease; reintervention; patch material; branch pulmonary artery stenosis; systematic review

Abstract

Pulmonary artery stenosis remains a significant challenge following congenital heart disease surgery, often requiring pulmonary artery patch arterioplasty and subsequent reintervention due to recurrent obstruction. Although anatomical site and patch material have been proposed as potential determinants of long-term outcomes, their independent contributions remain uncertain. This systematic review aimed to evaluate the association between anatomical site and patch material and the risk of reintervention following pulmonary artery patch arterioplasty in patients with congenital heart disease. A systematic review was conducted according to the PRISMA 2020 guidelines. PubMed/MEDLINE, Embase, Scopus, Web of Science, and Cochrane CENTRAL were searched from inception through September 2026. Studies reporting reintervention outcomes after pulmonary artery patch augmentation were included. Due to heterogeneity in anatomical locations, patch materials, outcome definitions, and analytical approaches, the findings were synthesized narratively. Risk of bias was assessed using the ROBINS-I tool. Eighteen non-randomized studies involving 2,696 patients were included. Anatomical site demonstrated a consistent association with reintervention risk, with branch pulmonary artery reconstruction showing higher reintervention rates compared with main pulmonary artery reconstruction or transannular patch augmentation. Bilateral branch pulmonary artery involvement was also associated with an increased risk of reintervention. In contrast, the effects of patch material were inconsistent, with most comparative studies showing no significant differences among materials. The anatomical characteristics of pulmonary artery reconstruction appear to be stronger determinants of reintervention risk than patch material. Future multicenter studies with standardized outcome definitions and long-term follow-up are required to further clarify the potential effects of patch materials.



This is an open access article under the [CC BY-SA](https://creativecommons.org/licenses/by-sa/4.0/) license.

Copyright © 2026 by Author. Published by Publikasiku Publisher

INTRODUCTION

Pulmonary artery stenosis remains one of the most persistent challenges in congenital cardiac surgery. It may occur as an isolated lesion, as part of tetralogy of Fallot, pulmonary atresia with ventricular septal defect, single-ventricle pathways, or as an acquired consequence of prior shunts, pulmonary artery banding, or surgical repair. The obstruction may involve the main pulmonary artery, extend across the bifurcation, or involve the branch pulmonary arteries toward the hilum, with morphological variations ranging from discrete narrowing to diffuse hypoplasia. The physiological consequences are substantial. Persistent obstruction increases

right ventricular workload, reduces pulmonary blood flow to the affected lung, and in patients with single-ventricle physiology may compromise the low-resistance pulmonary vascular bed required for successful Glenn and Fontan circulation (Hiremath et al., 2021; Soquet et al., 2019).

Surgical patch augmentation remains the primary treatment option when lesions are proximal, extensive, or unsuitable for catheter-based intervention, and it is commonly performed concurrently with repair of the underlying congenital defect. Operative mortality in contemporary series is low (Ye et al., 2023). However, long-term durability remains a major concern. Recurrent or persistent stenosis at the augmented segment occurs frequently enough that reintervention, including balloon angioplasty, stent placement, or repeat surgery, has become a recognized component of long-term management (Cresalia et al., 2018). Each reintervention carries additional risks, and patients and families require realistic expectations regarding long-term outcomes after repair.

Two operative factors under the surgeon's control have been proposed as potential determinants of durability. The first is anatomical location. A patch placed on the main pulmonary artery or across the pulmonary annulus is positioned within a wider, higher-flow region with greater tissue availability. In contrast, a patch placed on a branch pulmonary artery involves a smaller vessel constrained by surrounding structures, including the bronchus and pericardial reflections, with lower flow conditions and greater relative growth demands during childhood development. Branch pulmonary artery development after palliation is variable and influenced by the source and magnitude of pulmonary blood flow, providing a physiological rationale for the potential importance of anatomical location (Santoro et al., 2009; Zhou et al., 2020).

The second factor is patch material. Materials currently used in clinical practice include autologous pericardium, glutaraldehyde-treated autologous pericardium, cryopreserved and decellularized allografts, bovine and equine pericardial patches, porcine small intestinal submucosa, and expanded polytetrafluoroethylene (ePTFE). These materials differ substantially in handling characteristics, host tissue response, durability, and cost (Chlupac et al., 2022). The biological rationale underlying newer materials is based on improving biocompatibility and reducing adverse tissue responses. Glutaraldehyde fixation may increase the risk of tissue calcification, which has led to the development of anticalcification treatments for bovine pericardial materials (Bell et al., 2019; Kaneko et al., 2022; Neethling et al., 2020). Decellularized scaffolds are designed to facilitate host cell repopulation and potentially support tissue remodeling and growth.

The challenge is that anatomical location and patch material are rarely evaluated simultaneously. Studies comparing materials often combine different anatomical sites, whereas studies examining anatomical risk factors frequently do not separate outcomes by patch material. Furthermore, material selection is not random; homograft and xenogeneic patches may be preferentially used for more complex branch pulmonary artery reconstructions. Consequently, material comparisons that do not account for anatomical location may incorrectly attribute outcomes to the patch material rather than the vascular site, while anatomical comparisons that ignore material effects may introduce similar confounding.

Differences in outcome denominators further complicate interpretation. Some studies report outcomes per patient, others per patch, and others per reconstructed anatomical site. A single patient may receive multiple patches, such as a transannular patch and bilateral branch pulmonary artery patches, within the same cohort. Therefore, event rates calculated per patient and per anatomical location are not directly interchangeable. Analyses using different denominators without clear justification may create misleading comparisons.

Follow-up duration also influences interpretation of outcomes. Recurrent stenosis after pulmonary artery patch augmentation is generally not an immediate postoperative event but

develops over months to years as children grow and patched segments may fail to accommodate somatic growth. A study reporting no failures at 12 months and another reporting substantial reintervention rates at 10 years may be observing similar biological processes at different stages of follow-up. This consideration is particularly important for studies describing early clinical experience with specific patch products.

Meanwhile, catheter-based interventions have continued to advance. Cutting balloon angioplasty and stent implantation are now established treatment options for branch pulmonary artery lesions, including lesions involving the bifurcation (Cobb et al., 2021; Fujita et al., 2024; Hiremath et al., 2019). This evolution has changed the interpretation of reintervention as an outcome measure. A catheter-based intervention reported in a recent cohort may not represent the same clinical event as a surgical reoperation reported in earlier decades, and changes in treatment thresholds over time may influence reported rates. Systematic reviews spanning different eras must account for these differences.

The clinical implications are significant. If anatomical location is the dominant determinant, the critical surgical consideration is the extent of reconstruction required within the branch pulmonary arteries, while postoperative management should emphasize surveillance of patients with branch reconstructions. If patch material is the dominant determinant, material selection becomes the primary consideration, and differences in material cost would need to be justified by measurable clinical benefits. At present, however, the available literature does not provide sufficient evidence to determine the relative contribution of these factors.

The existing literature consists predominantly of single-center retrospective studies, several of which report early experiences with specific patch products, alongside narrative reviews of patch materials. No systematic review has comprehensively evaluated anatomical location and patch material together using a standardized approach. This review was therefore conducted to identify studies reporting outcomes after pulmonary artery patch arterioplasty in congenital heart disease, evaluate the influence of anatomical location and patch material on reintervention, assess the risk of bias within the available evidence, and determine the certainty of conclusions that can be drawn from the current literature (Agarwal et al., 2022; Dodge-Khatami et al., 2012; Taksaudom et al., 2024).

METHOD

Protocol and reporting

This review was conducted and reported in accordance with the PRISMA 2020 statement. As all included studies were non-randomized, their methodological characteristics were assessed against the STROBE framework (von Elm et al., 2007). The findings were synthesized narratively following the SWiM reporting guideline for synthesis without meta-analysis (Campbell et al., 2020). A protocol was prepared for registration in PROSPERO and was included with this report. No modifications were made to the eligibility criteria or outcome definitions after completion of the searches.

Eligibility criteria

Studies were eligible if they enrolled patients of any age with congenital heart disease who underwent surgical patch augmentation of the pulmonary arterial tree, at the main pulmonary artery, across the pulmonary annulus, or at one or both branch pulmonary arteries, and if they reported reintervention. Reintervention was defined as any subsequent surgical reoperation or catheter-based balloon angioplasty or stent implantation directed at the augmented segment or at the pulmonary arteries. Comparative and single-arm designs were both eligible, since a single-arm series of a defined material contributes to the material question without an internal comparator. Case series of fewer than ten patients or ten patches were not eligible. Reviews, editorials, protocols, conference abstracts without a full report, computational and in-silico studies and animal studies were excluded, as were reports in which

the patch served as a tube graft rather than as a patch, reports of aortic or neo-aortic arch reconstruction in which pulmonary artery tissue was the donor material, and reports in which pulmonary artery outcomes could not be separated from other implant positions. No language or date restriction was applied.

Information sources and search

PubMed/MEDLINE, Embase, Scopus, Web of Science and Cochrane CENTRAL were searched from inception to 10 September 2026. The strategy combined four concept blocks: pulmonary artery anatomy, patch arterioplasty and its synonyms, congenital heart disease and its principal diagnoses, and reintervention, reoperation and outcome terms, using controlled vocabulary and free text adapted to each interface. The full strategy for every database, with the interface used, the date of execution and the number of records returned, is reproduced in the accompanying search strategy document. Reference lists of all included reports and of the narrative reviews identified during screening were hand-searched for further eligible studies.

Study selection

Records were deduplicated and then screened on title and abstract by two reviewers working independently against the eligibility criteria. Reports passing that screen were retrieved in full and assessed independently by the same two reviewers. Disagreement at either stage was resolved by discussion until consensus was reached, and no third adjudicator was required. Reasons for exclusion were recorded for every full-text report that did not meet the criteria. All eighteen included studies were read at full-text level before extraction.

Data extraction

Data were extracted independently in duplicate into a predefined 27-field ledger covering study identity, design, setting, enrolment period, population, sample size, anatomical site or sites of patch placement, patch material or materials, comparator, follow-up duration, the reintervention outcome and its definition, and the effect estimate as reported. Extracted values were compared between reviewers and discrepancies reconciled against the source. Every number was recorded together with the table, figure or paragraph from which it was taken. The PMID of every included study was confirmed to resolve in PubMed and the DOI in Crossref. Items not reported in a source were recorded as not reported and were never imputed.

Risk of bias assessment

Risk of bias was assessed with ROBINS-I, which is intended for non-randomised studies of interventions and was appropriate for every included study (Sterne et al., 2016). Each study was judged independently by two reviewers across the seven domains of confounding, selection of participants, classification of interventions, deviations from intended interventions, missing data, measurement of outcomes, and selection of the reported result, with an overall judgement of low, moderate, serious or critical. Disagreement was resolved by discussion. The Newcastle-Ottawa Scale was considered and set aside, because its star-based scoring does not separate the confounding structures that dominate this literature (Stang, 2010). The conduct of the review itself was checked against AMSTAR 2 (Shea et al., 2017).

Synthesis and certainty of evidence

Meta-analysis was prespecified as conditional on the included studies sharing a unit of analysis, an anatomical position and an outcome definition. That condition was not met. Studies report per patient, per patch and per implant location; they mix main pulmonary artery, transannular, branch and bifurcation positions; and the threshold for reintervention ranges from a protocolised echocardiographic gradient to undefined clinical judgement. Pooling across those differences would yield a precise number corresponding to no real quantity, so no pooled estimate was calculated. Findings were grouped by comparison, first by anatomical site and then by patch material, and within each group the direction of effect, the magnitude as reported and the consistency across studies were described. Certainty for each comparison was rated

with GRADE, starting at low for a body of non-randomised evidence and adjusted for risk of bias, inconsistency, indirectness, imprecision and large effect (Guyatt et al., 2011).

RESULTS AND DISCUSSION

Study selection

The five database searches returned 436 records: 96 from PubMed/MEDLINE, 121 from Embase, 108 from Scopus, 84 from Web of Science and 27 from Cochrane CENTRAL. One hundred and thirty-two duplicates and a further five records were removed before screening, leaving 299 records for title and abstract screening. Of these, 268 were clearly irrelevant and were excluded. Full text was sought for 31 reports and obtained for 28; three could not be retrieved. The 28 retrieved reports were assessed against the prespecified criteria and 10 were excluded: three described no pulmonary artery patch arterioplasty or the wrong procedure, two reported no extractable reintervention outcome, two did not report patch material separately, one presented a mixed congenital heart disease cohort from which pulmonary artery data could not be separated, one was a duplicate or overlapping cohort, and one had an ineligible design or insufficient clinical data. Eighteen studies met all criteria and were included. Hand-searching the reference lists of the included reports and of the narrative reviews identified during screening yielded no further eligible study. The flow of records is given in Table 1.

Table 1. Flow of records through the review, reported according to PRISMA 2020.

Stage	Detail	n
Identification	Records identified from PubMed/MEDLINE	96
	Records identified from Embase	121
	Records identified from Scopus	108
	Records identified from Web of Science	84
	Records identified from Cochrane CENTRAL	27
	Total records identified from databases	436
Records removed before screening	Duplicate records removed	132
	Records removed for other reasons	5
Screening	Records screened on title and abstract	299
	Records excluded as clearly irrelevant	268
Retrieval	Full-text reports sought for retrieval	31
	Reports not retrieved (full text unavailable)	3
Eligibility	Reports assessed against the prespecified criteria	28
Reports excluded with reasons	No pulmonary artery patch arterioplasty or wrong procedure	3
	No extractable reintervention outcome	2
	Patch material not reported separately	2
	Mixed congenital heart disease cohort without separable pulmonary artery data	1
	Duplicate or overlapping cohort	1
	Ineligible study design or insufficient clinical data	1
	Total full-text reports excluded	10
Included	Studies included in the review	18

Note. Searches covered each database from inception to 10 September 2026. All eighteen included studies were read at full-text level before data extraction. Hand-searching the reference lists of the included reports and of the narrative reviews identified during screening produced no further eligible study. The itemised list of the ten excluded full-text reports, each with its individual reason, is held by the review team and accompanies the submission as a supplementary file.

Characteristics of included studies

The 18 included studies were published between 2012 and 2026 and together report 2696 patients across the seventeen studies that state a total denominator; one study did not report its

sample size. Fourteen were retrospective cohorts, three were retrospective case series and one was a prospective post-market cohort with a retrospective historical control. All were single-centre. Seven were conducted in the United States, three in Germany, two in South Korea, and one each in Sweden, Canada, Poland, Saudi Arabia and Turkey. Enrolment periods ran from two to twenty-eight years, and median or mean follow-up from roughly sixteen months to 13.8 years. Populations were predominantly infants and young children. Tetralogy of Fallot or a variant of it accounted for the largest cohorts, with hypoplastic left heart syndrome and pulmonary atresia with ventricular septal defect prominent in the single-ventricle series. Anatomical position was reported in twelve studies and patch material in fifteen. Full characteristics are given in Table 2, and the distribution of patch sites and materials across the included cohorts in Table 3.

Table 2. Characteristics of the eighteen included studies.

Study, country	Design and enrolment period	Population and n	Patch site	Patch material	Follow-up
von Stumm 2023, Germany	Retrospective cohort, 2012 to 2018	Biventricular CHD with PA stenosis, 156	Main PA or transannular 131; branch PA 25	ePTFE 99, equine pericardium 34, autologous pericardium 25, bovine pericardium 5	Mean 4 (SD 2) years
Lewis 2023, Sweden	Retrospective cohort, 1993 to 2020	Pulmonary arterial tree arterioplasty, 217	Bifurcation to distal branches; 153 unilateral and 159 bilateral patches	Autologous pericardium 166, pulmonary homograft 126, other 21	Median 13.8 years
Ebert 2020, United States	Retrospective cohort, 2000 to 2014	PA reconstruction, 180 patients and 214 sites	Main PA 80 sites; branch PA 134 sites	Branch homograft 92, bovine pericardium 44, autologous pericardium 41, porcine submucosa 37	Median 3.72 years
Cresalia 2018, United States	Retrospective cohort, 10-year period	Biventricular CHD with branch PA stenosis, 135	Branch PA, unilateral and bilateral	Not reported separately	Median 4.0 years
Hopkins 2014, United States	Prospective cohort with historical control, 2009 to 2012 and 2006 to 2009	Congenital cardiovascular reconstruction, 208	Pulmonary arterioplasty, 100 of 120 patches	Decellularised allogeneic PA patch versus cryopreserved allograft or synthetic	Intermediate term
Bonilla-Ramirez 2023, United States	Retrospective cohort, 2008 to 2017	Single-ventricle pulmonary arterioplasty, 59	Branch PA during staged palliation	Decellularised versus non-decellularised allogeneic PA patch	To pre-Fontan assessment
Murin 2021, Germany	Retrospective cohort, 2016 to 2019	Branch PA augmentation, 96	Branch PA, 147 locations	Decellularised equine pericardium	Median 20 months
Fraint 2016, United States	Retrospective cohort, 2004 to 2013	PA patch augmentation, total n not reported	PA augmentation, site not reported separately	Extracellular matrix versus standard patch	Longer in the standard patch group

Study, country	Design and enrolment period	Population and n	Patch site	Patch material	Follow-up
Wilder 2016, Canada	Retrospective cohort with risk-adjusted modelling, 2000 to 2012	Complete tetralogy of Fallot repair, 434	Branch PA; hilar versus proximal versus unaugmented	Not reported separately; strategy defined by extent of augmentation	10-year freedom from reintervention
Kim 2016, South Korea	Retrospective case series, 2004 to 2015	Postoperative PA stenosis, 28	Right PA 5, left PA 10, bilateral 13	Sutureless patch angioplasty	Mean 60.9 (SD 33.1) months
Gladki 2026, Poland	Retrospective case series, 2023 to 2024	PA or RVOT reconstruction, 25	Main PA, right PA, left PA and RVOT	Extracellular matrix patch	Median 483 days
Haney 2022, United States	Retrospective cohort, 2012 to 2019	Congenital cardiac surgery, 309 patients and 408 patches	PA repair in 181 of 408 patches	Small intestinal submucosal ECM, four-ply 376 and two-ply 32	Median 3.9 years
Weixler 2022, Germany	Retrospective cohort, 2016 to 2020	Patch implantation, 201 patients and 314 locations	Left or right PA 153, main PA 18, transannular or RVOT 20	Decellularised equine pericardium	Median 29.7 months
Elassal 2021, Saudi Arabia	Retrospective cohort, 2017 to 2020	Congenital cardiac surgery, 111	Main PA 26, right PA 7, left PA 9 of 144 patches	Equine pericardium 83 versus bovine pericardium 61	Not quantified
Kim 2014, South Korea	Retrospective cohort, from 2007	Tetralogy of Fallot with pulmonary stenosis, 42	Proximal left PA using a main PA anterior wall flap	Autologous pericardium 34, bovine pericardium 8	Mean 26.4 (SD 18.6) months
Lofland 2012, United States	Retrospective case series, 2009 to 2010	Neonates and infants, 44 patients and 46 patches	RVOT and PA reconstruction	Decellularised allograft PA patch	Early outcomes
Patel 2021, United States	Retrospective cohort, 1986 to 2017	Arterial switch operation, 403	PA reconstruction in pantaloon configuration	Fresh autologous pericardium	Median 8.6 years
Onalan 2022, Turkey	Retrospective cohort, period not stated	Unifocalisation for PA/VSD/MAPCA, 48	Central and branch PA during unifocalisation	Patch augmentation 30 versus pericardial roll 10	Not quantified

Note. CHD, congenital heart disease; ECM, extracellular matrix; ePTFE, expanded polytetrafluoroethylene; MAPCA, major aortopulmonary collateral artery; PA, pulmonary artery; RVOT, right ventricular outflow tract; SD, standard deviation; VSD, ventricular septal defect. Counts refer to patients unless stated as patches or locations. Entries recorded as not reported reflect the source publication and were not imputed.

Table 3. Reintervention by patch site and patch material in the single cohort reporting the full cross-tabulation.

Patch site	Patch material	Patches implanted, n	Patches reintervened, n	Reintervention rate, %
Transannular	ePTFE	70	6	9

Patch site	Patch material	Patches implanted, n	Patches reintervened, n	Reintervention rate, %
Main pulmonary artery	Autologous pericardium	9	1	11
	Equine pericardium	15	0	0
	Bovine pericardium	4	2	50
	ePTFE	24	3	13
	Autologous pericardium	9	0	0
Left pulmonary artery	Equine pericardium	7	0	0
	Bovine pericardium	0	0	0
	ePTFE	3	3	100
	Autologous pericardium	5	3	60
	Equine pericardium	8	7	88
Right pulmonary artery	Bovine pericardium	1	1	100
	ePTFE	2	2	100
	Autologous pericardium	3	2	67
	Equine pericardium	7	3	43
	Bovine pericardium	0	0	0

Note. ePTFE, expanded polytetrafluoroethylene. Values are reproduced exactly as published by von Stumm and colleagues, the only included study reporting reintervention cross-tabulated by both patch site and patch material. Two internal inconsistencies in the source are noted rather than corrected: the patch counts in this table sum to 167, against 163 patches at 170 patch sites reported elsewhere in the same report, and the material subtotals here give 26 autologous and 37 equine pericardial patches against 25 and 34 reported in that report's operative table. The reintervened patches sum to 33, which is compatible with the 30 patients who reached the composite endpoint because some patients had more than one patch reintervened. The gradient across sites is unaffected by these discrepancies: reintervention was 9% to 13% at transannular and main pulmonary artery positions and 43% to 100% at branch positions for every material used at both.

Risk of bias

No study was randomised and none was rated at low overall risk of bias. Five were rated moderate and thirteen serious. Confounding dominated. In every cohort the patch material was selected by the operating surgeon according to availability, vessel calibre and the difficulty of the reconstruction, so material is systematically related to the lesion it treats. Selection of participants added bias where cohorts were restricted to survivors with an intact patch at discharge, or where patients with early failure were removed from the follow-up denominator. Missing data recurred as a concern in studies that did not state what proportion of the enrolled cohort contributed to the reintervention analysis. Measurement of the outcome was generally sound, since reintervention is an objective and recorded event, and one cohort applied explicit echocardiographic thresholds before proceeding to angiography and multidisciplinary review.

Anatomical site as a determinant of reintervention

Four studies compared reintervention by anatomical position and all four pointed the same way. The largest site-stratified analysis reported freedom from the composite reintervention endpoint at five years of 92% (SD 3) for patches placed on the main pulmonary artery or across the annulus against 25% (SD 9) for patches placed on one or both branches. Branch position remained independently associated with reintervention after adjustment for weight and staged repair, with an adjusted hazard ratio of 11.44 (95% CI 4.60 to 26.41) (von Stumm et al., 2023). A cohort of 214 reconstruction sites found a hazard ratio of 0.41 (95% CI 0.16 to 1.07, $P = 0.068$) for the main pulmonary artery site relative to branch sites, consistent in direction although the interval crossed unity (Ebert et al., 2020). In a cohort of 314 implant locations, 47 of 53 patch-related reinterventions (88.7%) occurred in a pulmonary artery position, which accounted for much of the material implanted but a disproportionate share of the failures (Weixler et al., 2022). A cohort followed for a median of 13.8 years found reintervention in 26.6% of lesions spanning both proximal and distal segments against 21.1% of purely proximal lesions, a smaller difference that did not reach significance (Lewis et al., 2023).

Laterality behaved consistently in the two studies that examined it. Bilateral branch stenosis carried an adjusted hazard ratio of 2.8 ($P = 0.005$) relative to unilateral disease in 135 patients with biventricular physiology, in which neonatal age at operation was the other independent risk factor (Cresalia et al., 2018). In the 28-year cohort, reintervention occurred in 46 of 159 patches placed for bilateral lesions (28.9%) against 24 of 153 placed for unilateral lesions (15.7%), $P < 0.01$ (Lewis et al., 2023).

The extent of augmentation, as distinct from its position, was addressed in one risk-adjusted analysis of 434 tetralogy of Fallot repairs. Carrying the patch to the hilum was associated with a risk-adjusted 10-year freedom from branch reintervention of 73%, against 87% for limited extension arterioplasty and 91% for vessels left unaugmented, and the patch group showed reduced time-related branch growth and higher right ventricular pressure (Wilder et al., 2016). Two small series reported low reintervention after technique-specific reconstruction of a single branch: balloon angioplasty in 4 of 42 patients and no reoperation after left pulmonary artery angioplasty using an anterior wall flap of the main pulmonary artery (Kim et al., 2014), and in 1 of 28 patients with no reoperation after sutureless patch angioplasty (Kim et al., 2016). A series of 403 arterial switch operations using a single pantaloon patch technique of fresh autologous pericardium reported pulmonary arterioplasty as the most common reoperation at 11 of 403 (2.7%), at a median of 3.3 years (Patel et al., 2021).

Patch material as a determinant of reintervention

Eleven studies bore on material, and the picture is markedly less consistent. Three cohorts with an internal material comparison found no association between patch type and reintervention. Freedom from reintervention did not differ across autologous pericardium, pulmonary homograft and a heterogeneous group of other materials over a median 13.8 years ($P = 0.29$) (Lewis et al., 2023). Patch type was unrelated to reintervention across branch homograft, bovine pericardium, autologous pericardium and porcine intestinal submucosa (overall $P = 0.197$), with autologous pericardium carrying a hazard ratio of 0.36 (95% CI 0.10 to 1.33) against homograft at a unit cost difference of 6105 United States dollars (Ebert et al., 2020). Reintervention-free survival did not differ between extracellular matrix and standard patch material ($P = 0.12$) (Fraint et al., 2016).

Two comparative studies reported a material effect. Bovine pericardium was independently associated with reintervention in the site-stratified cohort, with an adjusted hazard ratio of 4.45 (95% CI 1.29 to 15.41). That estimate rests on five bovine patches, and the interval is correspondingly wide (von Stumm et al., 2023). Decellularised allogeneic pulmonary artery patch was associated with higher freedom from reintervention than non-

decellularised allogeneic patch in 59 single-ventricle patients, with a hazard ratio of 0.36 (95% CI 0.13 to 0.90), in a comparison in which shunt strategy differed between the groups (Bonilla-Ramirez et al., 2023). A prospective cohort of 106 patients receiving decellularised allogeneic patches recorded no device-related reoperation against a 14.0% patch failure rate in an immediately preceding historical cohort of 100 patients ($P < 0.0001$), a contrast separated by era (Hopkins et al., 2014). An early series of 44 patients receiving the same class of patch reported no device-related death or adverse event over approximately one year (Lofland et al., 2012).

Single-material cohorts contributed performance data without a comparator. Decellularised equine pericardium gave freedom from patch-related reoperation or stent implantation per location of 85.8% (95% CI 76.2 to 91.7) at 12 months and 78.7% (95% CI 65.9 to 87.2) at 24 months in 147 branch locations, in a cohort where 89.6% of procedures were redo operations (Murin et al., 2021). The same material across a wider range of positions gave 91.5% (95% CI 86.7 to 94.6) at 12 months and 85.2% (95% CI 78.9 to 89.6) at 24 months (Weixler et al., 2022). Small intestinal submucosal extracellular matrix required surgical reintervention in 10 of 408 patches (2.5%) and percutaneous reintervention in 27 of 408 (6.6%) over a median 3.9 years, with no difference between four-ply and two-ply construction (Haney et al., 2022). A series of 25 patients receiving an extracellular matrix patch reported no patch-related restenosis or dilation over a median 483 days, in a cohort the authors describe as too small and too briefly followed to support comparative conclusions (Gładki et al., 2026). A cohort comparing equine and bovine pericardium across mixed positions recorded recurrent main pulmonary artery stenosis in 3 of 16 equine and 2 of 10 bovine patches, with a single branch recurrence and no reoperation for patch-related complications (Elassal et al., 2021). In unifocalisation for pulmonary atresia with ventricular septal defect and major aortopulmonary collateral arteries, patch augmentation and a pericardial roll did not differ in reintervention frequency ($P = 0.65$), although all reinterventions in the roll group were unilateral while 41.7% in the patch group were bilateral (Onalan et al., 2022). The synthesis by comparison is set out in Table 4.

Table 4. Synthesis of findings by comparison and outcome domain

Comparison	Studies, n	Reported results	Direction	Consistency
Branch pulmonary artery versus main pulmonary artery or transannular patch site	4	von Stumm: freedom from reintervention 25% (SD 9) at branch versus 92% (SD 3) at main site at 5 years, adjusted HR 11.44 (95% CI 4.60 to 26.41). Ebert: main site HR 0.41 (95% CI 0.16 to 1.07), $P = 0.068$. Weixler: 47 of 53 reinterventions (88.7%) in a pulmonary artery position. Lewis: reintervention 26.6% for lesions spanning proximal and distal segments versus 21.1% proximal only	Favours the main pulmonary artery or transannular position	Consistent in direction across all four studies
Bilateral versus unilateral branch involvement	2	Cresalia: adjusted HR 2.8, $P = 0.005$ for bilateral stenosis. Lewis: reintervention 46 of 159 patches (28.9%) bilateral versus 24 of 153 (15.7%) unilateral, $P < 0.01$	Favours unilateral involvement	Consistent across both studies
Extent of branch augmentation in tetralogy of Fallot	1	Wilder: risk-adjusted 10-year freedom from branch reintervention 73% for extensive hilar augmentation, 87% for limited extension arterioplasty and 91% for unaugmented native vessels, $P < 0.01$; branch growth reduced and	Favours a restrained augmentation strategy	Single study, not corroborated

Comparison	Studies, n	Reported results	Direction	Consistency
		right ventricular pressure higher in the patch group		
Technique-specific reconstruction of a single branch	2	Kim 2014: balloon angioplasty in 4 of 42 (9.5%) and no reoperation after anterior-wall-flap angioplasty. Kim 2016: balloon angioplasty in 1 of 28 (3.6%) and no reoperation after sutureless patch angioplasty	Low reintervention in selected patients	Consistent, but from two small single-centre series
Bovine pericardium versus other patch materials	3	von Stumm: bovine pericardium independently associated with reintervention, adjusted HR 4.45 (95% CI 1.29 to 15.41), based on 5 patches. Ebert: bovine pericardium HR 1.43 (95% CI 0.52 to 3.92) versus homograft, overall patch-type P = 0.197. Ellassal: recurrent main pulmonary artery stenosis in 2 of 10 bovine versus 3 of 16 equine pericardial patches	Possible disadvantage, driven by a single small stratum	Inconsistent; only one study reached significance
Decellularised versus non-decellularised allogeneic patch	3	Bonilla-Ramirez: HR 0.36 (95% CI 0.13 to 0.90) favouring the decellularised patch. Hopkins: 0 device-related reoperations among 106 patients versus 14 of 100 (14.0%) in a historical control cohort, P < 0.0001. Lofland: no device-related adverse event among 44 patients	Favours the decellularised allogeneic patch	Directionally consistent, but both comparative studies are at serious risk of bias
Extracellular matrix versus conventional patch material	4	Fraint: no difference in reintervention-free survival, P = 0.12. Ebert: porcine submucosa HR 1.24 (95% CI 0.41 to 3.71) versus homograft. Haney: surgical reintervention in 10 of 408 patches (2.5%) and percutaneous reintervention in 27 of 408 (6.6%). Gladki: no patch-related restenosis among 25 patients over a median 483 days	No detectable difference	Consistent null across the comparative studies
Autologous pericardium versus pulmonary homograft	2	Lewis: freedom from reintervention similar across autologous pericardium, pulmonary homograft and other materials, P = 0.29. Ebert: autologous pericardium HR 0.36 (95% CI 0.10 to 1.33) versus homograft, at a unit cost of 0 versus 6105 United States dollars	No detectable difference in reintervention, with a large cost difference	Consistent null across both studies
Decellularised equine pericardium, single-material cohorts	2	Murin: freedom from reoperation or stent implantation per location 85.8% (95% CI 76.2 to 91.7) at 12 months and 78.7% (95% CI 65.9 to 87.2) at 24 months. Weixler: 91.5% (95% CI 86.7 to 94.6) at 12 months and 85.2% (95% CI 78.9 to 89.6) at 24 months	Performance comparable to other xenogeneic materials	Consistent between the two cohorts
Patch augmentation versus pericardial roll during unifocalisation	1	Onalan: no difference in pulmonary artery reintervention, P = 0.65; all reinterventions in the roll group were unilateral against 41.7% bilateral in the patch group	No detectable difference in frequency	Single small study, not corroborated

Comparison	Studies, n	Reported results	Direction	Consistency
Standardised pulmonary artery reconstruction after the arterial switch operation	1	Patel: pulmonary arterioplasty was the commonest reoperation at 11 of 403 (2.7%), at a median 3.3 years, with a pantaloon patch of fresh autologous pericardium used throughout	Low reoperation rate with a standardised technique in a low-risk position	Single study, no internal material comparison

Note. CI, confidence interval; HR, hazard ratio; SD, standard deviation. Results are reported as they appear in each source. No pooled estimate was calculated, because the included studies differ in unit of analysis (patient, patch or implant location), in anatomical position, in patch material and in the definition and ascertainment of reintervention. Synthesis follows the SWiM reporting guideline for synthesis without meta-analysis

Certainty of evidence

Certainty was rated low for the comparison of branch against main pulmonary artery position and for the comparison of bilateral against unilateral involvement. Both start low as non-randomised evidence, were downgraded for risk of bias or imprecision, and were upgraded for the size and consistency of the effect. Certainty was very low for every material comparison and for the single study of augmentation extent. The overall incidence of reintervention was rated low.

Discussion

This review asks a narrow question of eighteen non-randomised studies: how much of the risk of later reintervention after pulmonary artery patch arterioplasty attaches to where the patch is placed, and how much to what it is made of. The literature answers asymmetrically. Position behaves as a strong and reproducible determinant. Material does not.

Every study that compared reintervention by anatomical position found the branches to fare worse than the main pulmonary artery or the transannular segment, and in the one cohort that stratified cleanly by site the adjusted hazard was roughly elevenfold (von Stumm et al., 2023). Taken singly the corroborating evidence is weaker, with an interval crossing unity in one cohort (Ebert et al., 2020) and a non-significant difference in another (Lewis et al., 2023). Taken together, four independent centres working with different materials, eras and case mix reached the same conclusion, and that convergence is itself informative. Laterality points the same way: bilateral involvement approximately doubled the hazard in both studies that examined it (Cresalia et al., 2018; Lewis et al., 2023).

Several explanations are plausible and none excludes the others. The branches are smaller vessels, so a given absolute degree of neointimal thickening or patch contraction costs a larger fraction of the lumen. They carry lower flow and lower wall shear stress than the main trunk, and branch growth after congenital heart surgery depends on the volume and distribution of pulmonary blood flow, so a segment already underperfused may be least able to remodel favourably around a patch (Santoro et al., 2009; Zhou et al., 2020). The branches are also tethered by the bronchus and the pericardial reflection, which limits how a patch can be shaped. Set against these is confounding by indication. Patients needing branch augmentation have more extensive disease, and more extensive disease predicts reintervention whatever is sewn in. The multivariable models in the included cohorts adjust for weight, age and staged repair but not for a direct measure of baseline lesion severity, so this cannot be excluded and probably accounts for part of the effect.

The finding on augmentation extent deserves separate weight because it runs against surgical instinct. In 434 tetralogy of Fallot repairs, carrying the patch to the hilum was associated with worse 10-year freedom from branch reintervention than limited extension arterioplasty or leaving the vessel alone, alongside reduced time-related branch growth and

higher right ventricular pressure (Wilder et al., 2016). Roughly 85% of hypoplastic branches left native in that cohort grew adequately without instrumentation. This is one risk-adjusted analysis of an unrandomised strategy, and the comparison partly reflects which vessels surgeons judged to need aggressive treatment. It nonetheless poses a question worth asking at the table: whether extensive prosthetic augmentation of a small vessel substitutes non-growing material for tissue that would have grown.

The material findings read as a null result rather than an absence of data. Three cohorts with internal comparisons and reasonable follow-up found no association between patch type and reintervention (Ebert et al., 2020; Frint et al., 2016; Lewis et al., 2023), and the single-material series of decellularised equine pericardium and extracellular matrix scaffolds report performance in the range those comparative cohorts would predict (Gładki et al., 2026; Haney et al., 2022; Murin et al., 2021; Weixler et al., 2022). The two positive signals deserve to be weighed on their own terms. The bovine pericardium association rests on five patches in a single cohort, with an interval running from 1.29 to 15.41, and it was not reproduced in the two other cohorts that used bovine pericardium (Ebert et al., 2020; Ellassal et al., 2021; von Stumm et al., 2023). The decellularised allogeneic advantage comes from a comparison in which shunt strategy differed between groups in a way that independently affects pulmonary artery growth (Bonilla-Ramirez et al., 2023), and from a historical control separated by era (Hopkins et al., 2014; Lofland et al., 2012). Neither will carry a change in material selection.

That null has a practical edge. Unit costs across these materials differ by more than two orders of magnitude, from nothing for untreated autologous pericardium to over six thousand United States dollars for a branch homograft patch, and one included cohort estimated that substituting cheaper alternatives would have saved several hundred thousand dollars across the series with no observable difference in reintervention (Ebert et al., 2020). If material does not measurably alter durability, then handling, availability, avoidance of a second surgical field and cost become legitimate primary criteria rather than secondary ones. That is a reading of the present evidence, not an argument for abandoning any particular material.

The biological case for engineered materials remains reasonable even where the clinical signal is absent. Glutaraldehyde fixation predisposes autologous and xenogeneic tissue to calcification (Kaneko et al., 2022), anticalcification treatment of bovine pericardium was developed to address it (Bell et al., 2019; Neethling et al., 2020), and decellularised scaffolds are designed to be repopulated by host cells and to grow with the child (Chlupac et al., 2022). What these series show is that whatever advantage those properties confer is smaller than the variation introduced by anatomy, case mix and technique, at the follow-up durations so far published. An advantage emerging only after a decade would not yet be visible in most of these cohorts, and the two longest-followed studies here are also the two least likely to reflect current materials.

Comparison across studies is complicated by the endpoint itself. Reintervention is a decision as much as an event. One cohort triggered angiography at a defined echocardiographic gradient and then reviewed the case in a multidisciplinary meeting (von Stumm et al., 2023); others state no threshold at all. Because catheter treatment of branch stenosis has become safer and more effective across the period these studies span (Cobb et al., 2021; Fujita et al., 2024; Hiremath et al., 2019), the threshold for acting has probably fallen, so an intervention counted in a 2023 cohort represents a less severe lesion than one counted in 1995. This biases cross-era comparison toward apparently worse outcomes in recent series, and the published data do not allow adjustment for it. It also argues for reporting haemodynamic outcomes alongside reintervention in future work.

Set against the wider literature these results are unsurprising, but they are rarely stated together. Narrative reviews of patch materials conclude consistently that no clinical standard has emerged and that each material trades handling, cost and host response against the others,

which is what a body of null comparative studies would predict. Series describing the natural history of branch disease after repair of tetralogy of Fallot, pulmonary atresia with ventricular septal defect and the arterial switch operation likewise report pulmonary arterioplasty among the commonest late reoperations, and report its frequency tracking the complexity of the original pulmonary arterial anatomy rather than the technique used (Dodge-Khatami et al., 2012; Patel et al., 2021; Soquet et al., 2019; Ye et al., 2023). Contemporary reports of transannular and right ventricular outflow tract reconstruction, where the patch sits in a wide high-flow segment, describe durable relief of obstruction with pulmonary regurgitation rather than restenosis as the dominant late problem, which is the mirror image of what the branch series report (Agarwal et al., 2022; Taksaudom et al., 2024). The convergence of these separate literatures on position rather than substance strengthens the inference drawn here.

Several limitations constrain what can be concluded. All eighteen included studies are single-centre and non-randomised, and thirteen carry a serious overall ROBINS-I rating, so residual confounding by lesion severity is present throughout and cannot be quantified. Three reports meeting the screening criteria could not be retrieved in full and may have qualified. No pooled estimate was calculated, so this review offers direction and approximate magnitude rather than a summary effect, and the reader should not read the elevenfold hazard from a single cohort as a pooled quantity. Selective reporting is a genuine concern in a literature where several reports are early experience with a named product, and a centre whose early experience was poor has less incentive to publish it. The included cohorts span 1993 to 2026, over which both materials and catheter alternatives changed substantially, and no analysis here adjusts for era. Finally, twelve of the eighteen studies report anatomical position and material in a form that does not permit the two to be separated within the study, which is precisely the limitation this review set out to characterise and could not overcome.

What would move the field is clear enough. A multicentre registry analysis using the patch site as the unit of analysis, with a prespecified reintervention definition anchored to a haemodynamic threshold, baseline vessel Z-scores recorded at the index operation, and follow-up reaching the second decade, would separate the site effect from the material effect in a way no single-centre series can. Reporting outcomes separately for main pulmonary artery, transannular, unilateral branch and bilateral branch positions costs nothing and would make future synthesis possible. Until such data exist, the defensible position is that branch and bilateral reconstructions should be expected to need surveillance and often reintervention, and that patch material should be chosen on grounds other than an unproven durability advantage.

CONCLUSION

Across eighteen non-randomized studies of pulmonary artery patch arterioplasty in patients with congenital heart disease, anatomical site emerged as the more consistent determinant of reintervention risk. Patches placed on the branch pulmonary arteries, particularly in cases involving bilateral branch reconstruction, were associated with higher reintervention rates than patches placed on the main pulmonary artery or across the pulmonary annulus. This association was consistently observed across studies that directly compared anatomical locations. In contrast, patch material was not consistently associated with reintervention risk across comparative cohorts. The reported associations were limited by small sample sizes and potential confounding related to surgical era, underlying anatomy, and prior palliative procedures. The certainty of evidence was low for anatomical site comparisons and very low for patch material comparisons.

These findings should be considered hypothesis-generating. They suggest that the anatomical characteristics of the reconstructed pulmonary arteries may have greater prognostic importance than the specific patch material used. The results also support structured surveillance strategies following branch and bilateral pulmonary artery augmentation rather

than relying on symptom-driven evaluation alone. In the absence of demonstrated superiority of any specific material, considerations such as surgical handling properties, availability, and cost may reasonably guide material selection. Future prospective multicenter studies using the reconstructed anatomical site as the unit of analysis, predefined reintervention criteria, and long-term follow-up extending into the second postoperative decade are required to determine whether patch material has an independent effect on outcomes that is smaller than the influence of anatomical factors.

REFERENCES

- Agarwal, A., Al Amer, S. R., Al Tarif, H., Ismael, A. A., Alshaiji, A. F., Arulselvam, V., et al. (2022). Long-term outcomes of Tetralogy of Fallot in the Kingdom of Bahrain. *Heart Views*, 23(2), 78–85. https://doi.org/10.4103/heartviews.heartviews_77_21
- Bell, D., Prabhu, S., Betts, K., Justo, R., Venugopal, P., Karl, T. R., et al. (2019). Durability of tissue-engineered bovine pericardium (CardioCel®) for a minimum of 24 months when used for the repair of congenital heart defects. *Interactive CardioVascular and Thoracic Surgery*, 28(2), 284–290. <https://doi.org/10.1093/icvts/ivy246>
- Bonilla-Ramirez, C., Aggarwal, V., Atyam, M., Qureshi, A. M., Heinle, J. S., & McKenzie, E. D. (2023). Decellularized vs. non-decellularized allogeneic pulmonary artery patches for pulmonary arterioplasty. *Seminars in Thoracic and Cardiovascular Surgery*, 35(4), 722–730. <https://doi.org/10.1053/j.semtevs.2022.07.005>
- Campbell, M., McKenzie, J. E., Sowden, A., Katikireddi, S. V., Brennan, S. E., Ellis, S., et al. (2020). Synthesis without meta-analysis (SWiM) in systematic reviews: Reporting guideline. *BMJ*, 368, l6890. <https://doi.org/10.1136/bmj.l6890>
- Chlupac, J., Matejka, R., Konarik, M., Novotny, R., Simunkova, Z., Mrazova, I., et al. (2022). Vascular remodeling of clinically used patches and decellularized pericardial matrices recellularized with autologous or allogeneic cells in a porcine carotid artery model. *International Journal of Molecular Sciences*, 23(6). <https://doi.org/10.3390/ijms23063310>
- Cobb, H., Spray, B., Daily, J., Dossey, A., & Angtuaco, M. J. (2021). Cutting balloon angioplasty on branch pulmonary artery stenosis in pediatric patients. *Catheterization and Cardiovascular Interventions*, 98(3), 526–532. <https://doi.org/10.1002/ccd.29803>
- Cresalia, N. M., Armstrong, A. K., Romano, J. C., Norris, M. D., Yu, S., Rocchini, A. P., et al. (2018). Long-term outcomes after surgical pulmonary arterioplasty and risk factors for reintervention. *The Annals of Thoracic Surgery*, 105(2), 622–628. <https://doi.org/10.1016/j.athoracsur.2017.06.012>
- Dodge-Khatami, A., Mavroudis, C., Mavroudis, C. D., & Jacobs, J. P. (2012). Past, present, and future of the arterial switch operation: Historical review. *Cardiology in the Young*, 22(6), 724–731. <https://doi.org/10.1017/S1047951112001746>
- Ebert, N., McGinnis, M., Johnson, W., Kuhn, E. M., Mitchell, M. E., & Tweddell, J. S., et al. (2020). Comparison of patch materials for pulmonary artery reconstruction. *Seminars in Thoracic and Cardiovascular Surgery*, 33(2), 459–465. <https://doi.org/10.1053/j.semtevs.2020.09.011>
- Elassal, A. A., Al-Radi, O. O., Zaher, Z. F., Dohain, A. M., Abdelmohsen, G. A., Mohamed, R. S., et al. (2021). Equine pericardium: A versatile alternative reconstructive material in congenital cardiac surgery. *Journal of Cardiothoracic Surgery*, 16(1), 110. <https://doi.org/10.1186/s13019-021-01494-y>
- Fraint, H. Y., Richmond, M. E., Bacha, E. A., & Turner, M. E. (2016). Comparison of extracellular matrix patch and standard patch material in the pulmonary arteries. *Pediatric Cardiology*, 37(6), 1162–1168. <https://doi.org/10.1007/s00246-016-1413-8>

- Fujita, K. T., Barry, O. M., Torres, A. J., Crystal, M. A., & Turner, M. E. (2024). Simultaneous stent implantation for pulmonary artery bifurcation stenosis in infants. *Journal of Invasive Cardiology*, 36(9). <https://doi.org/10.25270/jic/24.00097>
- Gładki, M., Bednarek, P. R., Węclewska, A., Urbanowicz, T., Olasińska-Wisniewska, A., & Jemielity, M. (2026). Extracellular matrix tissue patch for pulmonary artery repair in pediatric cardiac surgery: A single-center experience. *Journal of Clinical Medicine*, 15(3). <https://doi.org/10.3390/jcm15031177>
- Guyatt, G., Oxman, A. D., Akl, E. A., Kunz, R., Vist, G., Brozek, J., et al. (2011). GRADE guidelines: 1. Introduction—GRADE evidence profiles and summary of findings tables. *Journal of Clinical Epidemiology*, 64(4), 383–394. <https://doi.org/10.1016/j.jclinepi.2010.04.026>
- Haney, L. C., Ahmed, H. F., Dani, A., Chin, P., Thangappan, K., Madsen, N., et al. (2022). More than 400 uses of an intestinal submucosal extracellular matrix patch in a congenital heart program. *The Annals of Thoracic Surgery*, 114(4), 1475–1483. <https://doi.org/10.1016/j.athoracsur.2021.06.087>
- Hiremath, G., Qureshi, A. M., Meadows, J., & Aggarwal, V. (2021). Treatment approach to unilateral branch pulmonary artery stenosis. *Trends in Cardiovascular Medicine*, 31(3), 179–184. <https://doi.org/10.1016/j.tcm.2020.02.001>
- Hiremath, G., Qureshi, A. M., Prieto, L. R., Nagaraju, L., Moore, P., Bergersen, L., et al. (2019). Balloon angioplasty and stenting for unilateral branch pulmonary artery stenosis improve exertional performance. *JACC: Cardiovascular Interventions*, 12(3), 289–297. <https://doi.org/10.1016/j.jcin.2018.11.042>
- Hopkins, R. A., Lofland, G. K., Marshall, J., Connelly, D., Acharya, G., Dennis, P., et al. (2014). Pulmonary arterioplasty with decellularized allogeneic patches. *The Annals of Thoracic Surgery*, 97(4), 1407–1412. <https://doi.org/10.1016/j.athoracsur.2013.12.005>
- Kaneko, S., Isoda, S., Aoyama, T., Goda, M., Yasuda, S., Shibuya, T., et al. (2022). Rapid anticalcification treatment for glutaraldehyde-fixed autologous tissue in cardiovascular surgery. *Journal of Cardiothoracic Surgery*, 17(1), 138. <https://doi.org/10.1186/s13019-022-01895-7>
- Kim, H., Chan Sung, S., Choi, K. H., Lee, H. D., Ban, G. H., Kim, G., et al. (2016). Sutureless patch angioplasty for postoperative pulmonary artery stenosis in congenital cardiac surgeries. *The Annals of Thoracic Surgery*, 101(3), 1031–1036. <https://doi.org/10.1016/j.athoracsur.2015.09.083>
- Kim, H., Sung, S. C., Chang, Y. H., Lee, H. D., & Park, J. A. (2014). Early and midterm outcomes of left pulmonary artery angioplasty using an anterior wall flap of the main pulmonary artery in tetralogy of Fallot repair. *The Journal of Thoracic and Cardiovascular Surgery*, 148(6), 2597–2601. <https://doi.org/10.1016/j.jtcvs.2013.10.060>
- Lewis, M. J., Malm, T., Hallbergson, A., Ramgren, J. J., & Liuba, P. (2023). Evaluation and comparison of patch materials used for pulmonary arterioplasty in pediatric congenital heart surgery. *JTCVS Open*, 15, 424–432. <https://doi.org/10.1016/j.xjon.2023.05.007>
- Lofland, G. K., O'Brien, J. E., Gandy, K. L., Dennis, P. A., Marshall, J. A., Mastbergen, R. K., et al. (2012). Initial pediatric cardiac experience with decellularized allograft patches. *The Annals of Thoracic Surgery*, 93(3), 968–971. <https://doi.org/10.1016/j.athoracsur.2011.09.039>
- Murin, P., Weixler, V. H. M., Kuschnerus, K., Romanchenko, O., Lorenzen, V., Nordmeyer, J., et al. (2021). Pulmonary artery augmentation using decellularized equine pericardium (Matrix Patch™): Initial single-centre experience. *European Journal of Cardio-Thoracic Surgery*, 60(5), 1094–1101. <https://doi.org/10.1093/ejcts/ezab183>
- Neethling, W., Rea, A., Forster, G., & Bhirangi, K. (2020). Performance of the ADAPT-treated CardioCel® scaffold in pediatric patients with congenital cardiac anomalies: Medium to

- long-term outcomes. *Frontiers in Pediatrics*, 8, 198. <https://doi.org/10.3389/fped.2020.00198>
- Onalan, M. A., Cicek, M., Rum, M., Yurdakok, O., Ozdemir, F., Korun, O., et al. (2022). Unifocalization with pericardial roll technique in pulmonary atresia with ventricular septal defect and major aortopulmonary collateral arteries. *Journal of Cardiac Surgery*, 37(9), 2642–2650. <https://doi.org/10.1111/jocs.16656>
- Patel, P. M., Herrmann, J. L., Bain, E., Ladowski, J. M., Colgate, C., Rodefeld, M. D., et al. (2021). Risk factors for reoperation after arterial switch operation. *World Journal for Pediatric and Congenital Heart Surgery*, 12(4), 463–470. <https://doi.org/10.1177/21501351211009768>
- Santoro, G., Capozzi, G., Caianiello, G., Palladino, M. T., Marrone, C., Farina, G., et al. (2009). Pulmonary artery growth after palliation of congenital heart disease with duct-dependent pulmonary circulation: Arterial duct stenting versus surgical shunt. *Journal of the American College of Cardiology*, 54(23), 2180–2186. <https://doi.org/10.1016/j.jacc.2009.07.043>
- Shea, B. J., Reeves, B. C., Wells, G., Thuku, M., Hamel, C., Moran, J., et al. (2017). AMSTAR 2: A critical appraisal tool for systematic reviews that include randomised or non-randomised studies of healthcare interventions, or both. *BMJ*, 358, j4008. <https://doi.org/10.1136/bmj.j4008>
- Soquet, J., Barron, D. J., & d'Udekem, Y. (2019). A review of the management of pulmonary atresia, ventricular septal defect, and major aortopulmonary collateral arteries. *The Annals of Thoracic Surgery*, 108(2), 601–612. <https://doi.org/10.1016/j.athoracsur.2019.01.046>
- Stang, A. (2010). Critical evaluation of the Newcastle-Ottawa scale for the assessment of the quality of nonrandomized studies in meta-analyses. *European Journal of Epidemiology*, 25(9), 603–605. <https://doi.org/10.1007/s10654-010-9491-z>
- Sterne, J. A., Hernán, M. A., Reeves, B. C., Savović, J., Berkman, N. D., Viswanathan, M., et al. (2016). ROBINS-I: A tool for assessing risk of bias in non-randomised studies of interventions. *BMJ*, 355, i4919. <https://doi.org/10.1136/bmj.i4919>
- Taksaudom, N., Thuropathum, P., Tepsuwan, T., Tantraworasin, A., Sittiwangkul, R., Phothikun, A., et al. (2024). Comparison of right ventricular outflow tract reconstruction techniques on mid-term pulmonic valve fate. *World Journal for Pediatric and Congenital Heart Surgery*, 15(4), 481–487. <https://doi.org/10.1177/21501351241237957>
- von Elm, E., Altman, D. G., Egger, M., Pocock, S. J., Gøtzsche, P. C., & Vandenbroucke, J. P. (2007). The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: Guidelines for reporting observational studies. *Annals of Internal Medicine*, 147(8), 573–577. <https://doi.org/10.7326/0003-4819-147-8-200710160-00010>
- von Stumm, M., Hildebrandt, T., Schaeffer, T., Heinisch, P. P., Georgiev, S., Wolf, C., et al. (2023). Mid-term results following pulmonary artery patch augmentation in congenital heart disease. *Translational Pediatrics*, 12(11), 1992–2000. <https://doi.org/10.21037/tp-23-382>
- Weixler, V. H. M., Kuschnerus, K., Romanchenko, O., Ovroutski, S., Cho, M. Y., Berger, F., et al. (2022). Mid-term performance of decellularized equine pericardium in congenital heart surgery. *Interactive CardioVascular and Thoracic Surgery*, 36(3). <https://doi.org/10.1093/icvts/ivac269>
- Wilder, T. J., Van Arsdell, G. S., Pham-Hung, E., Gritti, M., Hussain, S., Caldarone, C. A., et al. (2016). Aggressive patch augmentation may reduce growth potential of hypoplastic branch pulmonary arteries after tetralogy of Fallot repair. *The Annals of Thoracic Surgery*, 101(3), 996–1004. <https://doi.org/10.1016/j.athoracsur.2015.11.040>

- Ye, X. T., Buratto, E., Schulz, A., Macalister, S. J., Weintraub, R. G., Brizard, C. P., et al. (2023). Long-term outcomes of staged repair of tetralogy of Fallot. *The Journal of Thoracic and Cardiovascular Surgery*, 165(6), 2169–2180.e3. <https://doi.org/10.1016/j.jtcvs.2022.07.026>
- Zhou, T., Wang, Y., Liu, J., Wang, Y., Wang, Y., Chen, S., et al. (2020). Pulmonary artery growth after modified Blalock-Taussig shunt: A single center experience. *Asian Journal of Surgery*, 43(2), 428–437. <https://doi.org/10.1016/j.asjsur.2019.06.002>