A Meta-Analysis of, Bio-Digital Twin–Driven Advances in Patch Materials, Computational Modeling, and Tissue Engineering in Pediatric Cardiac Surgery and Heart Transplantation

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Abstract

Pediatric cardiac surgery and heart transplantation require durable, biocompatible, and growth-adaptive materials to ensure long-term clinical success. Conventional surgical patches such as ePTFE, Dacron, xenografts, and autologous pericardium are widely used but are associated with complications including thrombosis, calcification, inflammatory reactions, fibrosis, and aneurysmal dilatation. Bovine jugular vein and pulmonary homograft patches have been utilized for right ventricular outflow tract and pulmonary artery reconstruction; however, long-term degeneration remains a major concern.

Recent advances in imaging and computational technologies have significantly improved surgical planning and outcomes. Preoperative CT- and MRI-based three-dimensional segmentation, computational fluid dynamics (CFD), and finite element analysis (FEA) enable patient-specific modeling of cardiovascular anatomy and biomechanics. Studies have demonstrated that optimized patch sizing and geometry improve durability, with smaller patches showing superior longevity. Fluid–structure interaction (FSI) analysis further enhances biomechanical assessment, supporting the feasibility of personalized three-dimensional printing in pediatric cardiac surgery.

Building upon these developments, the emerging concept of the Bio-Digital Twin framework integrates patient-specific computational models with biomaterial design and biofabrication. In this approach, digital replicas of cardiac anatomy and hemodynamics are used to guide the optimization of scaffold geometry, mechanical properties, and microstructural features. Artificial intelligence–based optimization further enables prediction of growth-related changes and long-term biomechanical adaptation, facilitating the development of customized, growth-compatible patches.

Tissue engineering approaches have also emerged as promising alternatives. Decellularization techniques reduce immunogenicity of xenogenic and allogenic grafts, while glutaraldehyde fixation and anti-calcification mechanisms such as ADAPT improve material stability. Chitosan and fibrin scaffolds exhibit enhanced cellular growth potential. Microfabrication and electrospinning technologies enable the development of multilayered valvular constructs with improved cellular infiltration. Bioabsorbable valve conduits and pulmonary valve prostheses have also demonstrated potential for pediatric applications.

Historical and experimental studies, including prosthetic valve implantation and vascular graft development, laid the foundation for modern reconstructive techniques. The integration of biomaterials, computational modeling, and regenerative strategies through Bio-Digital Twin systems represents a paradigm shift toward personalized, growth-adaptive cardiac repair.

This review highlights the evolution of patch materials, computational modeling, tissue engineering, and Bio-Digital Twin technologies in pediatric cardiac surgery and heart transplantation, emphasizing their clinical relevance and future translational potential. Continued multidisciplinary research is essential to optimize long-term outcomes and reduce graft-related complications in pediatric patients.

Keywords

Pediatric cardiac surgery, heart transplantation, surgical patches, Bio-Digital Twin, computational fluid dynamics, tissue engineering, 3D modeling.