ORIGINAL RESEARCH PAPER

Cardiovascular

PATIENT-SPECIFIC COMPUTATIONAL SIMULATION IN CONGENITAL HEART DISEASE SURGERY: ADVANCED 3D RECONSTRUCTION, HAEMODYNAMIC MODELLING, COMPUTATIONAL FLUID DYNAMICS AND DIGITAL TWIN APPLICATIONS IN SINUS VENOSUS ATRIAL SEPTAL DEFECT

KEY WORDS: Congenital heart disease; sinus venosus ASD; PAPVR; computational fluid dynamics; hemodynamics; 3D printing; digital twin; artificial intelligence; surgical simulation.

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ABSTRACT

Congenital heart disease (CHD) represents one of the most complex fields of cardiovascular surgery because anatomical variation occurs at multiple spatial and physiological levels. Among the challenging lesions, sinus venosus atrial septal defect (SV-ASD) associated with partial anomalous pulmonary venous return (PAPVR) requires precise reconstruction of abnormal venous pathways, atrial septal anatomy, and systemic venous flow dynamics. Conventional imaging provides excellent anatomical information but often lacks the ability to predict postoperative hemodynamics or allow physical surgical rehearsal. Recent advances in computational modelling, three-dimensional (3D) printing, artificial intelligence (AI), virtual reality (VR), and digital twin technology have introduced a new paradigm of precision congenital cardiac surgery. Patient-specific computational models generated from CT/MRI datasets can reproduce anatomical geometry, simulate blood flow, calculate pressure gradients, estimate energy loss, and predict complications such as superior vena cava obstruction or pulmonary venous pathway stenosis. This review describes the complete workflow from image acquisition to digital reconstruction, computational fluid dynamics (CFD), fluid–structure interaction (FSI), 3D printed surgical models, and future AI-driven cardiac simulation. Mathematical foundations including Navier–Stokes equations, Reynolds number analysis, wall stress calculations, and haemodynamic energy modelling are discussed. The future development of real-time digital cardiac twins may enable virtual testing of surgical strategies before clinical intervention.

INTRODUCTION

Congenital cardiac surgery is fundamentally a three-dimensional reconstruction problem. Unlike acquired cardiac conditions where anatomy is relatively predictable, congenital abnormalities represent unique developmental variations requiring individualized repair strategies.

Sinus venosus atrial septal defect differs from common secundum ASD because the defect occurs near the superior vena cava (SVC)–right atrial junction and is commonly associated with anomalous pulmonary venous drainage.

The surgical objective is not simply closure of an atrial communication but restoration of:

1. unobstructed systemic venous return
2. correct pulmonary venous drainage
3. preservation of sinus node function
4. physiological right ventricular loading conditions

Traditional surgical planning relies on interpretation of two-dimensional CT/MRI sections. However, complex anatomy involving the SVC, anomalous pulmonary veins, and atrial septum requires spatial reconstruction.

Patient-specific simulation models provide an engineering solution by converting imaging data into interactive anatomical and physiological replicas.

Digital Transformation of Cardiac Imaging

Image Acquisition

The computational pipeline begins with high-resolution cardiac imaging.

Preferred modalities:

- ECG-gated CT angiography
- 3D cardiac MRI
- 4D flow MRI

The acquired image volume is represented mathematically as:

x,y,z,t

where:

- x,y,z = spatial coordinates
- t = cardiac phase
- I = image intensity

For CT imaging, tissue separation depends on Hounsfield Units:

Contrast-filled blood typically demonstrates higher HU values allowing segmentation.

Advanced Anatomical Segmentation

The segmentation process converts imaging voxels into anatomical structures.

The workflow includes:

Step 1

Blood pool extraction

Step 2

Chamber separation:

- right atrium
- left atrium
- SVC
- pulmonary veins

Step 3

Defect identification

Step 4

Surface reconstruction

The segmented geometry is converted into a triangular mesh:

M={V,E,F}

where:

- V = vertices
- E = edges
- F = triangular faces

High-resolution models may contain millions of elements.

Computational Fluid Dynamics (CFD) Haemodynamic Modelling

Blood flow simulation is governed by conservation laws.

Conservation of Mass

Conservation of Momentum

The Navier–Stokes equation – predicts (7-10):

- velocity distribution
- pressure variation

- turbulence
- vortex formation

Patient-Specific Boundary Conditions
Accurate CFD requires physiological input.

Inlet parameters:
- pulmonary venous flow
- SVC flow
- heart rate
- cardiac output

Flow relationship:
Cardiac output:
Reynolds Number and Turbulence Prediction
Flow characteristics are predicted using Reynolds number:

Interpretation:
- low Re → laminar flow
- high Re → disturbed flow

SV-ASD repairs may create regions of altered flow around:
- SVC pathway
- pulmonary venous baffle
- atrial reconstruction

Pressure Gradient and Energy Loss Modelling
The Bernoulli relationship:

important in detecting:
- SVC obstruction
- pulmonary venous narrowing

Energy loss due to turbulence:
Higher energy loss indicates inefficient postoperative flow.

Fluid–Structure Interaction (FSI)
Blood vessels and cardiac chambers are deformable structures.

The relationship between stress and strain:
FSI combines:
Fluid equations:
with structural mechanics:

Applications:
- predicting SVC compression
- evaluating baffle geometry
- estimating vessel compliance

3D Printing Technology in Congenital Cardiac Surgery
Digital models are exported as STL files.

Manufacturing methods:
- PolyJet printing
- stereolithography
- silicone casting
- TPU printing

Ideal materials reproduce:

Structure	Material property
atrium	flexible elastomer
veins	compliant polymer
valves	soft tissue mimic

Multi-material printing allows different colours and mechanical properties.

SV-ASD Specific Surgical Simulation

A high-fidelity SV-ASD model should reproduce:
- SVC override
- anomalous pulmonary venous entry
- atrial septal defect
- intended baffle pathway

Simulation allows:
- Warden procedure rehearsal
- patch sizing
- prediction of venous obstruction
- trainee education

Published studies have demonstrated improved understanding and planning using 3D printed congenital heart models [1–6].

Artificial Intelligence Integration
AI applications include:
Automated segmentation
Deep neural networks:
AI can identify:
- chambers
- vessels
- defects

Predictive modelling
Machine learning algorithms may predict:
- operative risk
- postoperative gradients
- optimal repair strategies

Digital Twin Concept
A congenital cardiac digital twin combines:
Anatomy +
Physics +
Haemodynamics +

Patient data
The model evolves continuously:
Future systems may simulate:
- alternative surgical repairs
- growth changes
- long-term outcomes

Future Innovations
Real-Time Surgical Digital Twins
Future operating rooms may integrate:
- live imaging
- CFD prediction
- augmented reality guidance

AI-Generated Surgical Planning
AI may automatically produce:
- repair strategies
- patch geometry
- postoperative predictions

Bioprinted Cardiac Models
Future tissues may incorporate:
- living cells
- vascular networks
- realistic mechanical properties

Growth-Predictive Models
Especially important in neonates and infants where anatomy changes rapidly.

SUMMARY

Patient-specific simulation represents the convergence of medicine, engineering, mathematics, and artificial intelligence. SV-ASD with PAPVR provides an ideal example where anatomy alone is insufficient and physiological prediction becomes essential.

Advanced CFD, FSI, 3D printing, and digital twin technology are transforming congenital cardiac surgery from experience-based planning toward predictive precision medicine.

The future of congenital heart surgery is expected to involve complete virtual testing of every repair before operation, reducing uncertainty and improving long-term outcomes.

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