# Relationship between flow patterns, energy efficiency and shape variations in the healthy pulmonary arteries via patient-specific numerical simulations

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## 1. Computational Fluid Dynamics in Biomedical Field

Computational Fluid Dynamics (CFD) have become a popular tool in various engineering fields due to their ability to predict and analyse fluid flow behaviour in complex geometries. However, the dynamics within the pulmonary arteries have been relatively underexplored. Such studies are important because of the complex nature of pulmonary artery hemodynamics, which can offer insights into diseases and interventions. The paper in question seeks to develop and validate methods to simulate blood flow in the Pulmonary Artery (PA), analyse its shape, and link these shape variations to hemodynamic measurements. The intention is to better understand normal flow dynamics, which can serve as a benchmark for identifying anomalies in patients. Originating from the heart, the main pulmonary artery (MPA) branches into the right (RPA) and left pulmonary arteries (LPA), which subsequently lead to smaller capillaries for gas exchange.

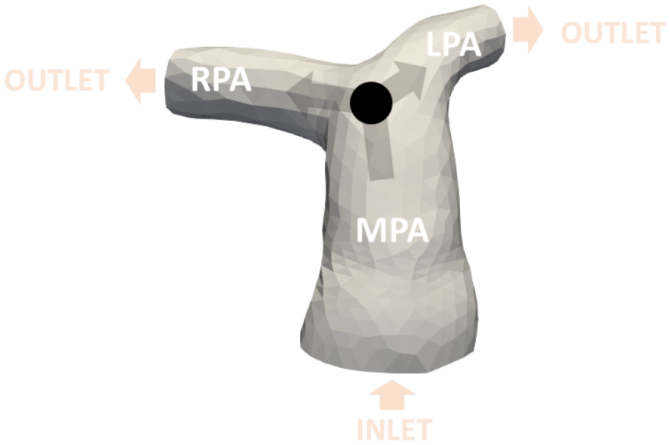


*Figure 1 : Pulmonary artery T shape as shown by a segmented 3D model*

### 1.1. Introduction to the Pulmonary Artery and Cardiovascular System

The pulmonary artery plays a vital role in the cardiovascular system by transporting deoxygenated blood from the heart to the lungs for oxygenation. Its structure and function are critical to ensuring efficient oxygen and nutrient supply throughout the body. A key component in the cardiovascular system is the cardiac cycle, consisting of systolic and diastolic phases, responsible for blood pumping. However, despite its importance, our understanding of the flow dynamics within the pulmonary artery, especially in healthy individuals, remains limited. Advanced imaging techniques and computational modelling can potentially offer more insights into these dynamics.

### 1.2. Imaging and CFD Methodology

Medical imaging, with a focus on Magnetic Resonance Imaging (MRI), is central to the study. MRI offers 3D, real-time images, especially the 4D-flow[1] technique, which is crucial for capturing details of blood vessels and their flow dynamics. Once these images are obtained, the CFD methodology involves several stages, from the initial image acquisition and segmentation to the simulation and post-processing of the data. At the heart of CFD are the Navier-Stokes equations, which help predict fluid motion. Some assumptions are made for these simulations, and the finite element method (FEM) is utilized for the mathematical calculations.

## 2. Methodology Overview

The study adopts a systematic approach to understand and analyse the pulmonary artery's flow dynamics. Beginning with the preparation of Computational Fluid Dynamics (CFD) simulations, anatomical models are processed, and necessary parameters and boundary conditions are set. This phase also integrates MRI data for better data visualization. The SimVascular® software is then utilized for simulations on a cluster, enabling the numerical modelling of blood flow in the pulmonary artery. Post simulation, results are processed to extract key quantities, with tools such as Paraview® and MATLAB® being vital for data processing and visualization. Simultaneously, a Statistical Shape Analysis (SSA) study is conducted using Deformetrica, producing numerical shape scores and establishing a correlation between flow dynamics and pulmonary artery shape.

[1] 4D-flow stands for the acquisition of space and time defined velocity vectors.

## 2.1. Data and Pre-processing

A dataset from 35 healthy adults, aged 19-45, was obtained through Cardiovascular Magnetic Resonance (CMR). This high-resolution CMR technique, known as 4D-flow, captured time-resolved three-dimensional velocity data. This data is organized into files containing velocity information, acquisition-related properties, and pulmonary artery geometries. For effective simulations, the raw surface representation of the pulmonary artery models requires refinement. This step involves manual processing with MeshMixer to address irregularities, particularly before integrating them into SimVascular®. For numerical calculations, the complex domains in CFD simulations are discretized, utilizing TetGen for mesh generation. The Global Mesh Edge Size (GMES) parameter is crucial for mesh refinement. Time discretization ensures an accurate numerical calculation while the Courant-Friedrichs-Lewy (CFL) condition is used to ensure the stability of the simulation, guiding the minimum time step size determinations. The integration schema used is the implicit and the time discretization size is 1/4000 seconds.

## 2.2. Post-Processing and Analysis

Following the simulations, scalar quantities are derived to simplify and interpret the complex data, which aids in understanding relationships between various variables. Automated Paraview macros are essential for processing and exporting results, with MATLAB® facilitating the deeper analysis. Despite the advantages of scalar quantities, dimensional analysis in both space and time offers more detailed insights into fluid behaviour. To manage large datasets, filtering based on mean kinetic energy curves identifies significant deviations. A deeper examination of kinetic energy at the inlet supports the results from this mean kinetic energy analysis. The study also introduces new scalar quantities that characterize each simulation independent of time and space, examining aspects such as energy losses, energy efficiency, vorticity, helicity, and the Q-criterion. The Q-criterion helps to identify vortical structures by isolating the asymmetric component of vorticity. These quantities and analyses provide comprehensive insights into the pulmonary artery's flow dynamics.

# 3. Results

## 3.1. CFD Analysis

The study used computational fluid dynamics (CFD) to evaluate the main pulmonary artery (MPA) under varying inlet conditions, concentrating on kinetic energy progression throughout the cardiac cycle. This energy demonstrated a direct proportionality with volume flow at the inlet, evidenced by parallels in acceleration, systolic peak, and deceleration phases. In the MPA, laminar flow during acceleration transitioned flow on the outer MPA wall at the systolic peak. Unique velocity patterns and significant pressure differentials arose during different cardiac phases. These patterns, combined with helicity analysis, indicate complex interactions between the blood flow and elements like the pulmonary valve. Vortical structures formed at key junctures, influenced by the curvature and pressure gradients, corroborated by findings like Dean vortices from other scientific works [1, 2, 3, 4].

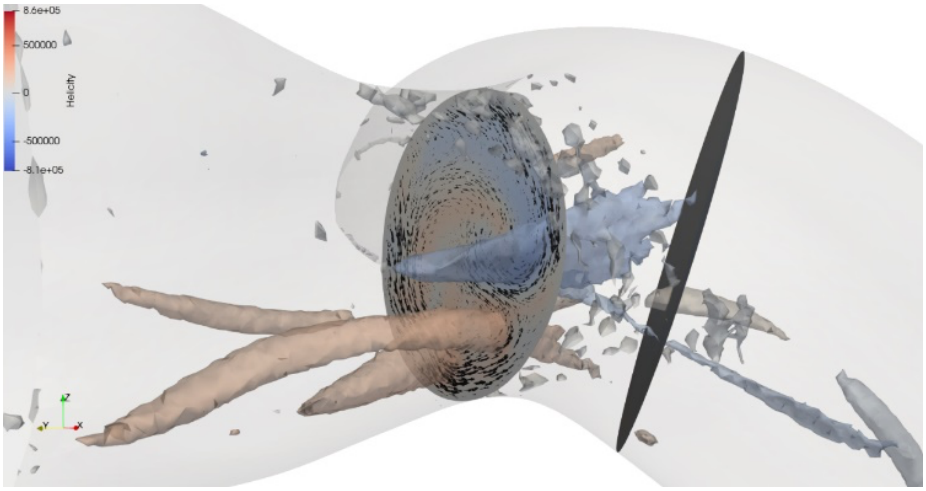


*Figure 2 : Vortical structure observed in the RPA during peak systole, emphasized using Q-criterion isosurfaces*

## 3.2. Flow Fields and Vortical Structures

Flow field examinations revealed distinct velocity and pressure patterns across the cardiac cycle. During acceleration, a uniform laminar flow was observed in the MPA. But as the cycle moved to the systolic peak, the flow became more concentrated towards the outer wall of the MPA. Alongside velocity patterns, pressure variations in the MPA were also noted, with significant differences appearing between the outer and inner walls of the MPA and the RPA/LPA split during different phases.

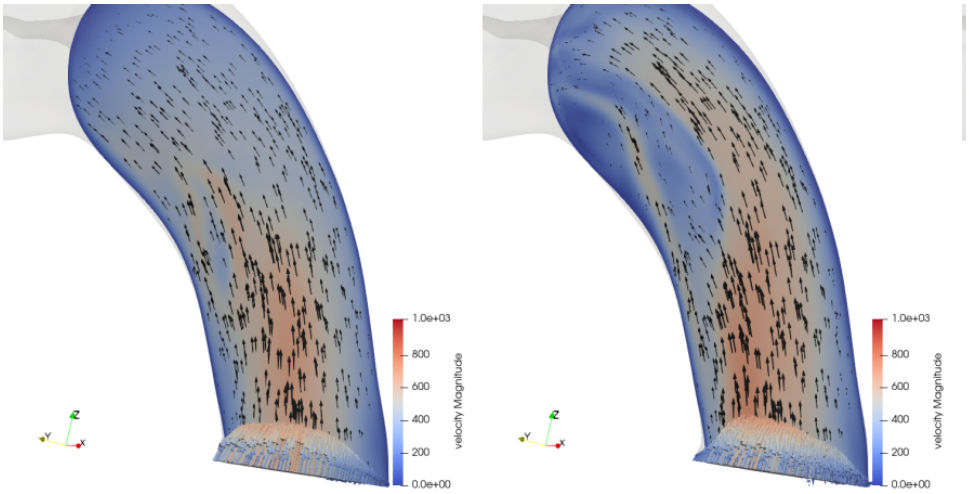


*Figure 3 : MPA velocity with in-plane vectors and 3D inlet conditions during acceleration (left) and peak systole (right)*

Additionally, helicity zones showcased the influence of the MPA's curvature on flow patterns. Vortical structures emerged as a critical element in this study. Primary and secondary vortices were observed at different times and locations, their formation influenced by curvatures and the associated pressure gradients.
Especially during the deceleration phase, swirling motions originating from the MPA's bifurcation and extending to the RPA and LPA became prominent.

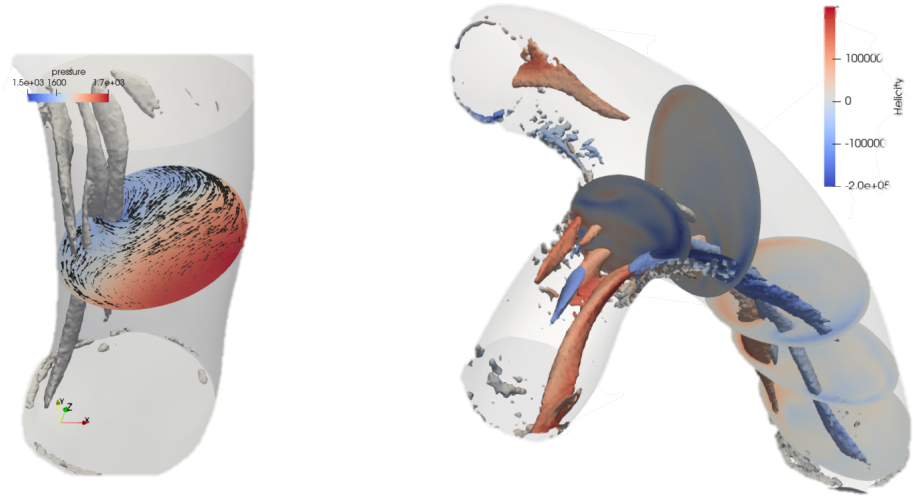


*Figure 4 : Formation of vortical structures during systole peak highlighted using Q-criterion isosurfaces*

### 3.3. Global Characterization Results

The global analysis aimed to correlate average kinetic energy in the pulmonary artery (PA) with other quantities. A notable finding was the absence of correlation between kinetic energy and two specific quantities, η (a measure of PA performance) and volume. Its performance (η) is assessed by comparing average kinetic energy during one cardiac cycle with energy losses. While the variability in inlet conditions posed challenges for broad generalizations, correlations were identified between volume, η, and Helicity, hinting at possible multidimensional relationships. Additionally, the study ventured into the correlation between different modes and quantities. The SSA analysis elucidated geometric impacts of various modes, with assumptions like mode 0 increasing the volume, and mode 3 reducing the MPA's curvature. The potential effects of these modes on PA performance were discussed, using η and vortical structures presence, suggesting that while some linear correlations exist, higher-order relationships might also be at play. The study concludes that further in-depth analysis is required to pinpoint the exact relationships among these variables.

## 4. Conclusion

This research seeks to bridge the knowledge gap in pulmonary artery flow dynamics, potentially enhancing clinical management of pulmonary vascular diseases. By merging computational fluid dynamics simulations with in-vivo data, the study delves deep into flow patterns and their causative factors using advanced tools like statistical shape analysis. While the study employs rigorous data processing techniques to ensure reliability, it acknowledges challenges like modeling assumptions and variability in in-vivo inlet conditions. As the field advances, refining simulation methods and exploring the physiological impact of observed patterns will be pivotal for early disease diagnosis and understanding.

## 5. Sources

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