# In-silico Model to Study the Role of Anomalous Origin of Coronary Arteries in Sudden Cardiac Death

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## Abstract

*Sudden cardiac death in athletes is often related to anomalies in coronary-arteries originù, which affect the coronary perfusion. These anomalies seems not associated with the processes inducing the sudden cardiac death, since no symptoms are observed even during intense physical activities. To analyze the physical processes induced by anomalous coronary artery origins an experimental setup has been proposed by Mousavi 2024 [1], reproducing the human ascending aorta, aortic sinuses of Valsalva, left, and right coronary arteries, including a first-hand trileaflet bioprosthetic aortic valve. To understand accurately the hydrodynamic processes, aortic pressures, coronary pressures, and coronary flows has been measured simultaneously, allowing us to evaluate coronary resistance and to setup numerical simulations useful for the modeling of the fluid dynamics in the whole coronary arteries. Piecewise-constant resistance parametrization is used in Windkessel-type models to derive coronary outflow. To test the capability of this approach, it is used to evaluate the boundary conditions of numerical simulations of the hydrodynamics in the Valsalva Sinuses and in the coronary arteries, showing an accurate simulation of the hydrodynamic structures, supporting the use of Windkessel-type outflow boundary conditions, based on pressure measurements.*

## 1. Introduction

Coronary arteries are vital blood vessels that provide oxygen and nutrients to the heart muscle. Originating from the base of the aorta in an area called the sinuses of Valsalva, these arteries are essential for the heart's function. Cardiovascular diseases, particularly sudden cardiac death (SCD), pose significant global health challenges and are among the leading causes of mortality and morbidity worldwide. In particular, anomalous origin of coronary arteries has been associated to SCD during sport activities, suggesting surgical intervention [2, 3], but the physiological processes including SCD are still uncertain. Hence, a comprehensive understanding of the complex hemodynamic within the aortic root and coronary arteries is essential for better diagnosis and treatment of coronary artery diseases (CAD).

The flow pattern and pressure distribution in the coronary arteries and aortic root can be accurately modelled in-vitro [1, 4, 5] or in-silico, using Computational Fluid Dynamics (CFD) [3, 6]. In the second case, the setting of boundary conditions (BCs) is critical for proper reproduction of dynamic fluid in vessels. In particular, to ensure a correct modelling of coronary perfusion, it is necessary to assign a flow BCs at the coronary outlets, synchronized appropriately with the other BCs. Mousavi [1] proposed one of the first in-vitro study providing synchronized pressure and flow measurements in the ascending aorta and the proximal part of both the coronaries. Pressure sensors were strategically placed at the aorta inlet, left coronary artery (LCA) outlet, right coronary artery (RCA) outlet, and aorta outlet, while a flow sensor measured coronary flow rates. Such measurement can be used to model and validate suitable boundary conditions for an accurate in-silico model.

As an alternative to using measured data, BCs can be modelled, taking care to include the effect of the resistance encountered by the flow. Advanced models, such as lumped parameter models, have been proposed including the coronary artery resistance and the arterial bed compliance, capillary resistance and intramyocardial pressure during ventricular contraction [6].

The aim of this paper is to develop and test a computational model that accurately represents coronary artery resistance at its boundaries. The BCs will be based on an electrical analog model, derived from the Windkessel model, synthesizing literature with the experimental data from [1]. The reliability of the obtained BCs will be tested through numerical simulations.

## 2. Experimental Data Analysis

The data from the experimental model were processed using MATLAB 2023b to obtain the resistance parametrization for each coronary. The signals of pressure

and flow have been divided into windows each corresponding to a cardiac cycle, obtaining four cycles of 2.6 seconds. Each cycle has been identified by analyzing the pressure waveform at the aortic tube outlet. Ensemble averaging has been performed for pressures and flows across cardiac cycles, obtaining the data reported in Figure 1, which show the dynamic relationship between coronary blood flow and aortic outlet pressure. A linear relationship is clearly evident throughout the cardiac cycle for the RCA, suggesting the assumption of a unique value for the RCA resistance parametrization. Instead, the LCA is characterized by large fluctuations, due to myocardial contraction.

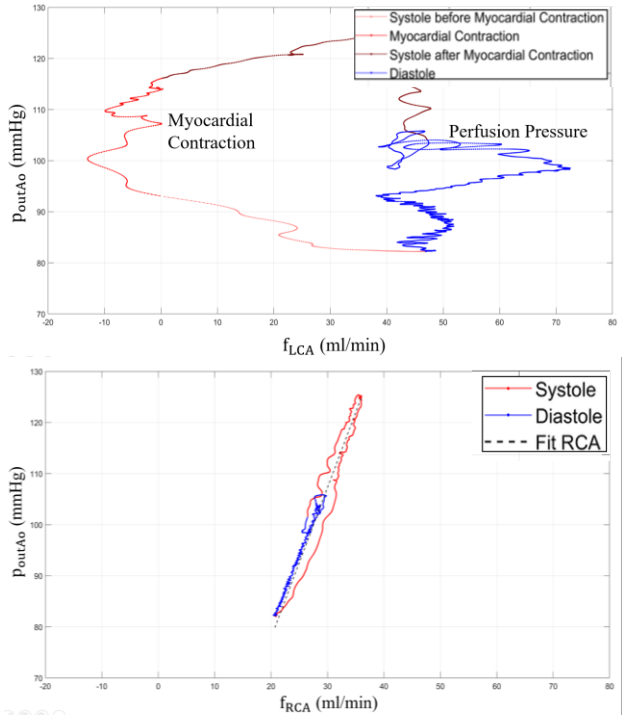


Figure 1. Dynamic relationship between coronary blood flow ($Q_{LCA}$, upper panel and $Q_{RCA}$ lower panel) and aortic outlet pressure ($p_{outAo}$).

Resistance for the left and right coronary arteries has been calculated using the equation:

$$R = \frac{\Delta P}{Q} \tag{1}$$

where $\Delta P$ is the pressure gradient between the inlet (measured) and outlet (evaluated using Bernoulli principle) of the coronary, while $Q$ is the measured coronary flow rate (see [7] for details). The obtained resistance has been filtered with a 4th-order Butterworth filter with a cutoff frequency of 70 Hz. This approach gives the results reported in Figure 2, which has been normalized during its entire duration.

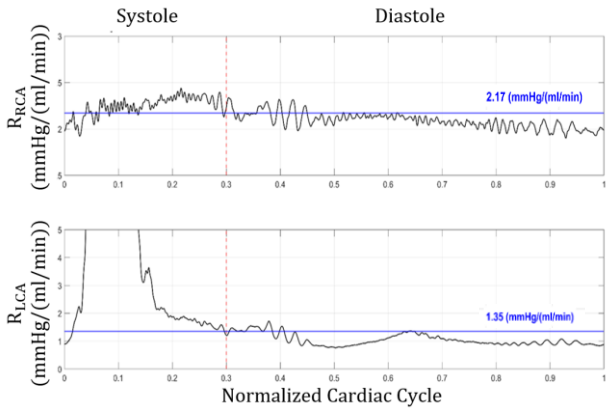


Figure 2. Resistance during the cardiac cycle for the RCA (upper panel) and LCA (lower panel). In blue is shown the mean value resistance.

As suggested by the results in Figure 1, RCA resistance can be properly approximated by its mean value, equal to 2,17 mmHg/(ml/min). Instead, the LCA resistance can be approximated by its mean value, equal to 1.35 mmHg/(ml/min), only out of the myocardial contraction. During myocardial contraction a peak resistance of 2400 mmHg/(ml/min) is reached in the LCA. This distinction is critical for accurately simulating coronary blood flow in CFD, as it reflects the varying physiological demands and mechanical influences within the cardiac cycle.

## 3. CFD Model

CFD models have been implemented using Ansys Fluent 2024 R1, using the same geometry of the experimental model that in [1] reproduced the human ascending aorta, aortic sinuses of Valsalva, left, and right coronary arteries, with rigid walls. The fluid has been modelled as incompressible laminar fluid; the model has been discretized with a mesh of 343011 elements, and two cycles had been simulated (see [7] for details). The flow in the numerical domain is driven by four BCs: pressures BC were assigned at the inlet and outlet of the aorta, while flow BCs were assigned at the outlet of the coronaries. As mentioned in the introduction two different coronary BCs have been used, while the same experimental pressure BCs have been used at the inlet and outlet of the aortic root, to test the proposed Windkessel-based BCs.

In the first case, the experimental measured data have been used as BCs. In the second case, BCs coronary outlets have been evaluated from pressures using the 3-element Windkessel model equation:

$$Q(t)\left(1+\frac{R_1}{R_2}\right)+CR_1\frac{dQ(t)}{dt}=\frac{P(t)-P_{out}}{R_2}+C\frac{dP(t)}{dt} \tag{2}$$

where $Q(t)$ is the flow, $R_1$ and $R_2$ are the resistances, $C$ the compliance, $P(t)$ is the pressure at the coronaries and $P_{out}$

is the reference pressure output. The flow at the RCA has been derived from measured pressure using a 2-element Windkessel model, incorporating resistance estimated from the experimental data.

The LCA flow has been evaluated with a combination of a 2-element Windkessel model (for non-contraction phase) and a 3-element Windkessel model (for contraction phase). The second has been parametrized using the mean value of the resistance out of the contraction and coupling the mean resistance with the peak resistance (see Eq. 2) during the contraction phase. For both models, the compliance has been evaluated with an optimization process, minimizing the deviation from the measured flow. In Table 1 are reported the evaluated values of resistances and compliance: the LCA mean resistance ($R_{LCA,mean}$), the LCA resistance peak during contraction ($R_{LCA,contr}$), the RCA mean resistance ($R_{RCA,mean}$), the LCA compliance ($C_{LCA}$) and the RCA compliance ($C_{RCA}$).

Table 1. The Windkessel Parameters used to estimate the mass flow rate in both coronaries.

| LCA | Windkessel Model Parameters | Value |
|---|---|---|
| | $R_{LCA,mean}$ | 1.35 mmHg/(ml/min) |
| | $R_{LCA,contr}$ | 2400 mmHg/(ml/min) |
| | $C_{LCA}$ | 0.6 ml/mmHg |
| RCA | Windkessel Model Parameters | Value |
| | $R_{RCA,mean}$ | 2.17 mmHg/(ml/min) |
| | $C_{RCA}$ | 0.686 ml/mmHg |

The estimated coronary blood flow using the Windkessel model aligns closely with experimental data, as shown in Figure 3, validating the model's accuracy in simulating coronary hemodynamic for both a 3-element model with LCA and a 2-element model with RCA.

Figure 4 and 5 show the velocity profiles in longitudinal section of the RCA, obtained using the Windkessel-modelled BCs and the experimentally measured BCs, respectively in the numerical simulations. Three different instants of the normalized cardiac cycle (0.5, 0.7, and 0.9) are considered, which are indicated in blue dashed vertical lines in the upper panel of Figure 3. Even if the profiles obtained with experimental data exhibit a smoother and more uniform flow pattern, with fewer fluctuations and disturbances compared to the simulated profiles, both the results of Figure 4 and 5 show the formation of a flow wave at the origin of the coronary artery (see 1st panels of Figure 4 and 5), which propagates and dissipates along the RCA (see 2nd and 3d panels of Figure 4 and 5). This demonstrate that the proposed Windkessel-based BCs enable the reproduction of physiological structures with CFD.

Additionally, fluid dynamic structures can be recognized within the Valsalva Sinuses. As the cycle progresses from 0.5 to 0.9 (see Figure 4), these jets evolve, creating complex vortex structures within the sinuses. These vortices play a crucial role in directing blood inflow into the coronary.

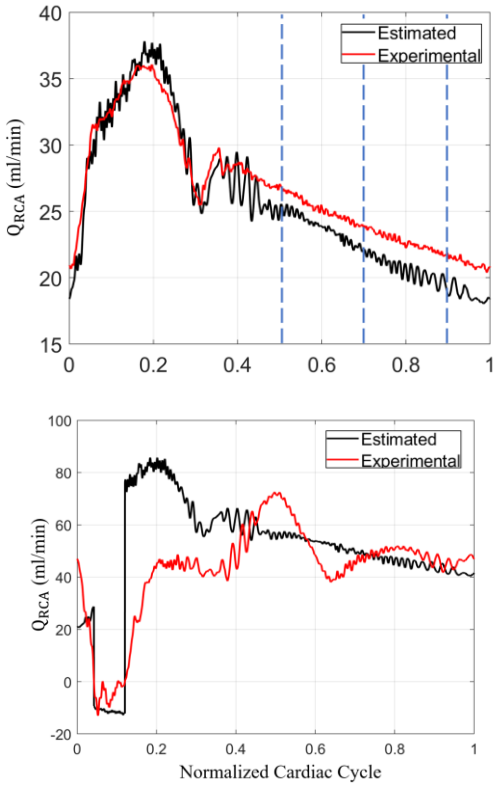


Figure 3. Comparison of the estimated coronary flow using the Windkessel model with the experimental data for the LCA (upper panel) and RCA (lower panel).

## 4. Conclusion

In conclusion, precise BCs in CFD simulations are essential for realistic and reliable results, offering deeper insights into coronary artery hemodynamics and contributing to advancements in cardiovascular research and prevention for SCD. The reported CFD simulations demonstrate that simple Windkessel-modeled BCs based on in-vivo or in-vitro measurements can be used in CFD simulations for replication physiological hemodynamic structures, even when outflow in the coronary arteries is not available, as long as appropriate compliance parameterization is available. In fact, the comparison of velocity profiles during diastole shows that these BCs enable the realistic propagation and dissipation of flow waves from the coronary origin along the vessel. The proposed approach can be used in upcoming work, including anomalous coronary artery origins.

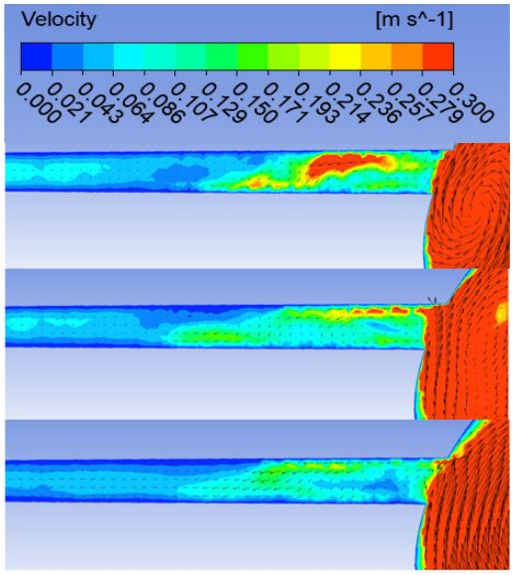


Figure 4. Velocity profile obtained from the simulation with the Windkessel-modeled BCs in the RCA in three different times of the normalized cardiac cycle: 0.5, 0.7 and 0.9 (from top to bottom).

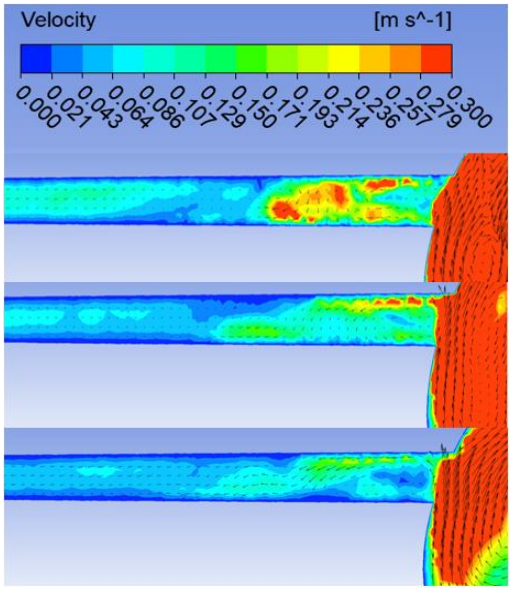


Figure 5. Velocity profile obtained from the simulation with the experimental data as BCs in the RCA in three different times of the normalized cardiac cycle: 0.5, 0.7, and 0.9 (from top to bottom).

## References

[1] S. M. Mousavi, "Experimental and Numerical Investigations in Sport-Related Cardiac Death" *Ph. D. dissertation, Polytechnic University of Marche, Ancona, 2024*.

[2] H. Agrawal, A. Lamari-Fisher, K. Hasbani, S. Philip, C. D. Fraser, and C. M. Mery, "Decision Making in Anomalous Aortic Origin of a Coronary Artery.". *Expert Review of Cardiovascular Therapy vol.21, no.3, pp. 177-191, 2023.*

[3] P. Angelini, "Novel Imaging of Coronary Artery Anomalies to Assess Their Prevalence, the Causes of Clinical Symptoms, and the Risk of Sudden Cardiac Death.". *Circulation: Cardiovascular Imaging vol. 7, no.4, pp. 747-754, 2014.*

[4] G. Querzoli, S. Fortini, S. Espa and S. Melchionna, "A Laboratory Model of the Aortic Root Flow Including the Coronary Arteries.". *Experiments in Fluids vol .57, no. 8, pp. 134, 2016.*

[5] M. C. F. Geven, V. N. Bohté, W. H. Aarnoudse, P. M. J. van den Berg, M. C. M. Rutten, N. H. J. Pijls, and F. N. van de Vosse, "A Physiologically Representative in Vitro Model of the Coronary Circulation.". *Physiological Measurement vol. 25, no. 4 pp. 891, 2004.*

[6] M. Cong, X. Xu, J. Qui, S. Dai, C. Chen, X. Qian, H. Zhang, S. Qin, and H. Zhan, "Influence of Malformation of Right Coronary Artery Originating from the Left Sinus in Hemodynamic Environment.", *BioMedical engineering OnLine vol. 19, no. 1, pp 59, 2020.*

[7] M. Gjika, "Modeling Coronary Artery Resistance for Numerical Simulation of the Aortic-Root Fluid-Dynamics and Coronary Perfusion", Master's thesis work, Polytechnic University of Marche, Ancona, 2024.

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