DOI: 10.15825/1995-1191-2025-4-103-109

HYBRID HEMODYNAMIC MODELING FOR OPTIMIZATION OF MECHANICAL CIRCULATORY SUPPORT SYSTEMS

A.I. Syrbu[1], *A.O. Shevchenko*[1, 2], *N.V. Grudinin*[1], *A.S. Buchnev*[1]

[1] Shumakov National Medical Research Center of Transplantology and Artificial Organs, Moscow, Russian Federation
[2] Sechenov University, Moscow, Russian Federation

Objective: to propose and justify approaches for improving the classical hemodynamic test bench, widely used to model the integration of mechanical circulatory support (MCS) systems. **Materials and methods.** The hemodynamic test bench consisted of multiple containers and resistors simulating systemic and pulmonary circulation, enabling the study of physiological conditions in heart failure (HF). The setup also included an auxiliary circulatory support pump and a pulsatile flow generator. **Results.** A mathematical model of the cardiovascular system was developed, capable of reproducing physiological states under conditions of pump-assisted circulation and pulsatile flow. Comparative evaluation of experimental and modeling results highlighted the advantages and limitations of different modeling methods. **Conclusion.** Based on these findings, strategies for further development of the hemodynamic test bench, aimed at enhancing its ability to simulate the impact of mechanical circulatory support on key hemodynamic parameters, were formulated and justified.

Keywords: mechanical circulatory support, hemodynamic test bench, mathematical modeling.

INTRODUCTION

Modern transplantology increasingly depends on engineering solutions designed to support the function of vital organs, including the heart [1, 2]. One of the most rapidly evolving fields involves the creation and optimization of mechanical circulatory support (MCS) systems, encompassing both extracorporeal and implantable pulsatile and continuous-flow pumps, as well as auxiliary devices for generating pulsatile blood flow [2–6].

Despite significant technological progress, one of the most critical stages in the development and clinical translation of MCS systems remains preclinical modeling and testing. Reproducing the physiological conditions under which these systems operate requires a high degree of precision, both in hydrodynamic performance and systemic physiological response [7, 8]. Consequently, continuous improvement of simulation platforms is essential, not only to accommodate the characteristics of novel devices, but also to integrate modern computational and mathematical modeling approaches.

The objective of this study is to substantiate proposals for the development of hemodynamic modeling complexes, using as an example the hemodynamic test bench designed and implemented at Shumakov National Medical Research Center of Transplantology and Artificial Organs [4, 5]. The work integrates the results of modeling, validation, and optimization of MCS parameters obtained by the authors, including a new technical device for generating pulsating flow [9–11].

MATERIALS AND METHODS

The hemodynamic test bench comprises an aortic (pulmonary artery) simulator, systemic and pulmonary hydraulic resistance, atrial reservoirs, an axial pump replicating the function of the left or right ventricles, an artificial ventricle simulator equipped with a pneumatic drive, and a sensor system for continuous monitoring of pressure and flow parameters. A schematic representation of the test bench configuration is presented in Fig. 1.

The physical component of the simulation complex – the hemodynamic test bench – enables the reproduction of key modes of cardiovascular system function through integration of mechanical and hydraulic elements. To enhance configurability, account for individual physiological variability, and model complex interaction scenarios with MCS devices, a mathematical model was developed. This model enables the prediction of hemodynamic responses to variations in device parameters, including those of the axial pump and pulsatile-flow generator (PFG) [9, 10].

The structure of the mathematical model (Fig. 2) consists of the following elements: left ventricle, left atrium, aortic, peripheral, and venous compartments, as well as coronary circulation, baroreceptor regulation, oxygen debt compensation, heart rate control circuits, and the aortic and mitral valves. In addition, the blocks describing the operation of the continuous flow pump and the pulsatile flow generator are highlighted with dotted lines [11].

Corresponding author: Arseniy Syrbu. Address: 1, Shchukinskaya str., Moscow, 123182, Russian Federation.
Phone: (915) 453-98-55. E-mail: s_arseniy@outlook.com

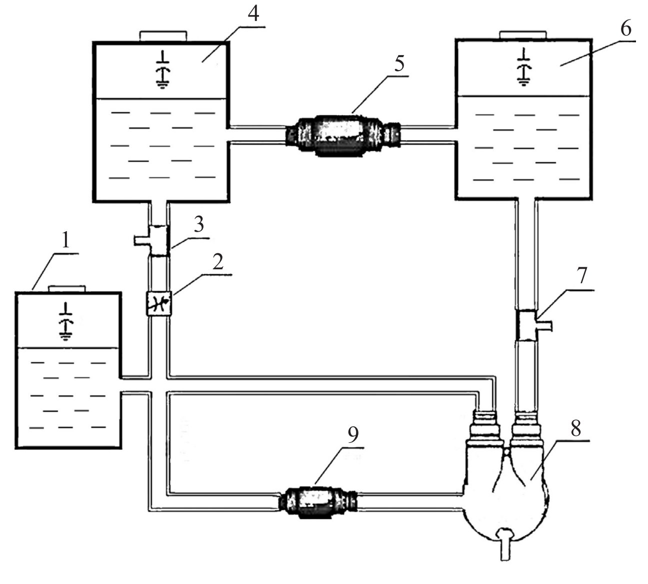

Fig. 1. Schematic diagram of the hemodynamic test bench: 1, arterial reservoir; 2, systemic hydraulic resistance; 3, arterial or pulmonary pressure sensor; 4, venous reservoir; 5, continuous-flow pump simulating systemic or pulmonary circulation; 6, reservoir simulating the pulmonary vein–left atrium system; 7, atrial pressure sensor; 8, artificial heart ventricle; 9, test VAD pump

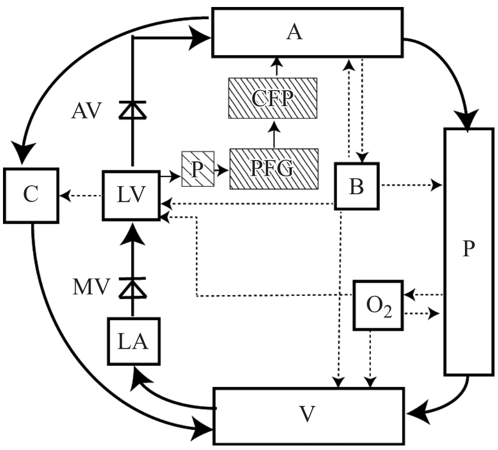

Fig. 2. Structural diagram of the mathematical model of the cardiovascular system with mechanical circulatory support. Abbreviations: LV, left ventricle; LA, left atrium; AO, aortic section; P, peripheral circulation; V, venous section; C, coronary vessels; B, baroreceptor regulation; O_2, oxygen debt regulation circuit; AV, aortic valve; MV, mitral valve; CFP, continuous-flow pump; PFG, pulsatile-flow generator

The diagram shows, with dotted lines, the added elements of the system: the continuous-flow pump, pulsatile flow generation devices, and a component simulating the occurrence of negative pressure in the left ventricle. Incorporating these modules – which represent the functional characteristics of MCS devices – into the previously developed mathematical model of the cardiovascular system makes it possible to account for their impact on key hemodynamic parameters.

RESULTS

The results of flow modeling through the MCS system obtained using the hemodynamic test bench are presented in Fig. 3.

For comparison, the results derived from the mathematical model under identical experimental conditions are shown in Fig. 4.

Analysis of the presented dependencies indicates that, although the obtained results are both qualitatively and quantitatively comparable, certain hydrodynamic phenomena are not fully captured by the model. Specifically, the lumped-parameter model fails to account for turbulent flow formation during the transition from systole to diastole and does not incorporate the non-Newtonian properties of blood.

On the other hand, the existing hemodynamic test bench cannot simulate specific physiological transitions, such as a shift from a state of rest to a state of physical exertion. Such constraints are typical of all bench-based hemodynamic systems.

In light of these limitations, recent years have seen increasing emphasis on the development of hybrid simulation platforms, integrating both physical test benches and computational mathematical models under a control system [12–18].

The results of this study make it possible to outline several proposals for optimizing the hemodynamic test bench developed at the Laboratory of Biotechnical Systems, Shumakov National Medical Research Center of Transplantology and Artificial Organs, with the overarching goal of enhancing the efficiency of MCS systems.

The goal of improving the test bench is to create a simulation test bench system that provides the ability to model the state of the cardiovascular system, taking into

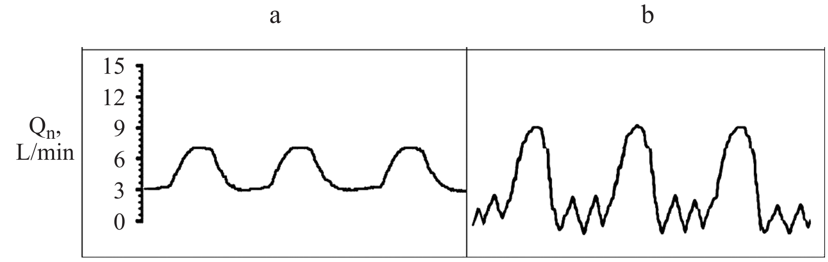

Fig. 3. Pump flow characteristics under continuous-flow conditions (a) and with connection to a pulsator (b), obtained on a hemodynamic stand. Interval = 1 s. Q_n – pump flow rate (L/min)

account heart failure, other pathologies, the level of physical activity, the presence of MCS systems, their characteristics, and modes of operation. At the same time, as shown by mathematical modeling results, it is essential to take into account the mechanisms of neurohumoral and baroreceptor regulation.

First of all, it is advisable to replace the existing analog controller of the heart simulator with a digital, reprogrammable real-time control module. At the same time, a set of algorithms for controlling the heart simulator can be pre-formed and tested on the mathematical model of the cardiovascular system developed in this work.

Additionally, the test bench should include controllable hydrodynamic resistances with high-precision pressure sensors. These components will enable closed-loop feedback control to account for the mechanisms of neurohumoral and baroreceptor regulation, similar to what was implemented in the mathematical model of the cardiovascular system developed in this work.

We recommend developing a pulsatile flow generator model with variable controlled pressure inside the chamber. Such a device would permit real-time tuning of generator parameters to reproduce blood flow that closely match the physiological characteristics of individual patients. Control signal parameters for the generator would be predefined in the mathematical model of the device.

The mathematical model described above can form the core of a hybrid (semi-natural) simulation platform. In this architecture the cardiovascular system's bulk hydraulics are realized on the hemodynamic test bench, while regulatory and adaptive mechanisms (baroreflex, neurohumoral feedback, exercise responses, etc.) are simulated in the computational module. Real-time measurements of pressure, flow and other state variables from the bench are streamed to the model, which computes corrective control signals and returns them to the bench to adjust resistances and chamber pressures.

A schematic overview of the proposed hybrid approach is shown in Fig. 5: solid lines denote fluid flows, and dotted lines indicate control signals from the computer part and back. A closely related concept has been previously discussed [19].

The following algorithm was developed to govern the operation of the proposed simulation test bench:

1) The model and test bench parameters are configured to simulate heart failure conditions;
2) The flow-pressure characteristics of the MCS device under investigation are entered into the model;
3) The test bench parameters are adjusted so that recorded pressures and flow rates correspond to clinical data;
4) It is then connected to a pulsatile flow generator (PFG);

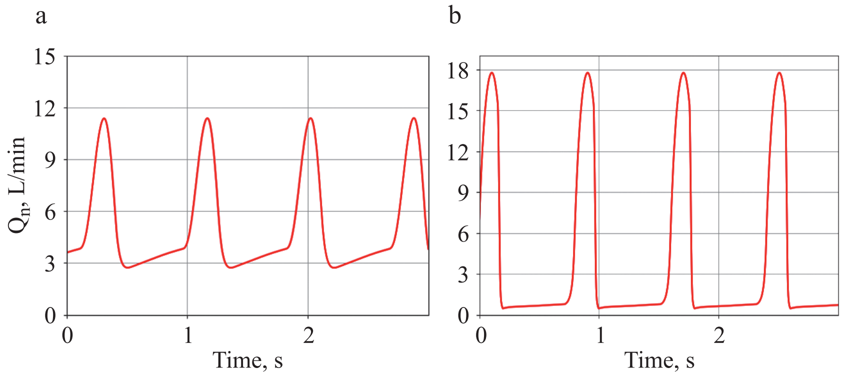

Fig. 4. Flow profiles through the pump under continuous-flow conditions (a) and with pulsator connection (b), obtained using a mathematical model. Interval = 1 s. Q_n – pump capacity (L/min)

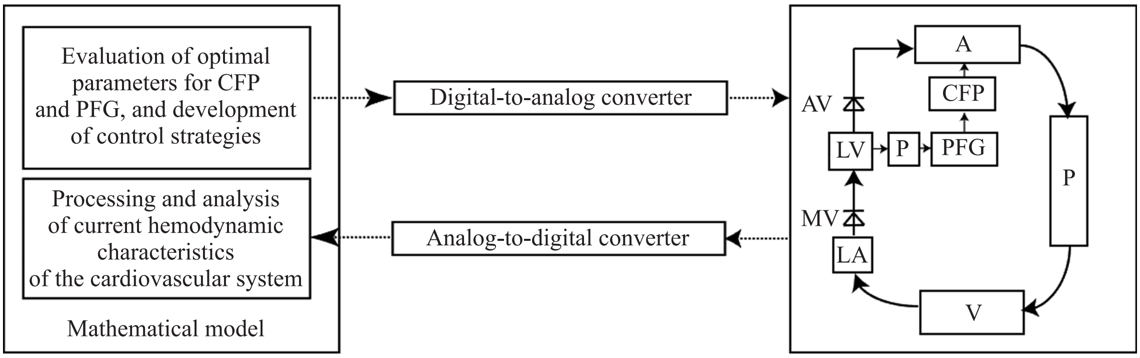

Fig. 5. Structural diagram of the proposed hybrid (semi-natural) simulation test bench

5) Experimental phase: A series of experiments is performed in which the parameters of the PFG, such as opening/closing pressures and hydraulic resistance, are systematically varied;
6) The resulting data are approximated and analyzed to determine the optimal pressure parameters within the PFG chamber and the maximum effective resistance of the generator and related elements;
7) The test bench settings are then adjusted in accordance with the identified optimal values;
8) A series of verification tests is conducted.

The core component of a next-generation computer model integrated into such a hybrid (semi-natural) simulation stand should be an intelligent analysis and control system capable of automatically analyzing hemodynamic data, recognizing the cardiovascular functional state of the system, and adaptively regulating the MCS parameters in real time. Such a computer model can be built on the basis of, for example, a multilayer neural networks and machine learning algorithms.

The following research directions should be identified as priority tasks for which the proposed hybrid modeling stand can be used:

1. Investigation of the rotor speed modulation algorithms aimed at increasing pulse pressure.
2. Investigation of the rotor speed modulation algorithms designed to ensure adaptive response to physical exertion and other conditions.
3. Study of the parameters of pulsatile-flow generation devices and their optimization.

Thus, the mathematical modeling of the cardiovascular system, incorporating the functional characteristics of MCS systems, enables the exploration of both existing and next-generation designs of continuous-flow pumps and pulsatile-flow generators. It also provides a framework for assessing the influence of various operational modes of these devices on the cardiovascular system under different conditions.

DISCUSSION

A comparison of results obtained from the hemodynamic test bench and from the mathematical model shows the need for a hybrid approach to more accurately characterize interactions between MCS devices and the cardiovascular system. Such an approach makes it possible to capture device-specific effects observed on the physical bench while simultaneously introducing physiologically meaningful feedback into the hydraulic system. Integrating physical and computational components within a single hybrid complex enables a closed-loop control architecture in which real-time data from the bench are streamed to the mathematical model, processed, and returned as control commands. This arrangement significantly broadens the functionality of the test bench and ensures a high level of physiological reliability of the experiments.

A review of the literature further corroborates the growing interest in the creation of hybrid simulation platforms among researchers in this field.

CONCLUSION

The development of hybrid simulation complexes marks a major advancement in the engineering support of extracorporeal circulation systems. The integration of a physical hemodynamic test bench with an adaptive mathematical model provides a new level of precision and flexibility in the testing, tuning, and validation of MCS systems.

Of particular relevance is the implementation of intelligent control algorithms enabling the personalization of MCS parameters. Furthermore, such systems can simplify and accelerate the preclinical evaluation of novel extracorporeal circulation systems.

Hybrid simulation complexes represent the foundation of a new generation of engineering medicine tools – systems that are intelligent, adaptive, and patient-centered.

The authors declare no conflict of interest.

REFERENCES

1. *Gautier SV.* Priority areas of scientific research in the field of transplantology and artificial organs. *Russian Journal of Transplantology and Artificial Organs*. (In Russ.). 2025; 27 (1): 6–7.
2. *Cameli M, Pastore MC, Campora A, Lisi M, Mandoli GE.* Donor shortage in heart transplantation: How can we overcome this challenge? *Front Cardiovasc Med*. 2022 Oct 17; 9: 1001002. doi: 10.3389/fcvm.2022.1001002.
3. *Kyriakopoulos CP, Kapelios CJ, Stauder EL, Taleb I, Hamouche R, Sideris K et al.* LVAD as a bridge to remission from advanced heart failure: current data and opportunities for improvement. *J Clin Med*. 2022 Jun 20; 11 (12): 3542. doi: 10.3390/jcm11123542.
4. *Itkin GP, Bychnev AS, Kuleshov AP, Drobyshev AA.* Haemodynamic evaluation of the new pulsatile-flow generation method *in vitro*. *Int J Artif Organs*. 2020 Mar; 43 (3): 157–164. doi: 10.1177/0391398819879939.
5. *Buchnev AS, Kuleshov AP, Esipova OYu, Drobyshev AA, Grudinin NV.* Hemodynamic evaluation of pulsatile-flow generating device in left ventricular assist devices. *Russian Journal of Transplantology and Artificial Organs*. 2023; 25 (1): 106–112. (In Russ.). https://doi.org/10.15825/1995-1191-2023-1-106-112.
6. *Itkin GP.* Ventricle assist device: past, present, and future nonpulsatile pumps. *Russian Journal of Transplantology and Artificial Organs*. 2009; 11 (3): 81–87. (In Russ.). https://doi.org/10.15825/1995-1191-2009-3-81-87.
7. *Fresiello L, Muthiah K, Goetschalckx K, Hayward C, Rocchi M, Bezy M et al.* Initial clinical validation of a hybrid in silico–*in vitro* cardiorespiratory simulator for comprehensive testing of mechanical circulatory support systems. *Front Physiol*. 2022 Oct 13; 13: 967449. doi: 10.3389/fphys.2022.967449.

8. *Pugovkin AA, Markov AG, Selishchev SV, Korn L, Walter M, Leonhardt S et al*. Advances in hemodynamic analysis in cardiovascular diseases investigation of energetic characteristics of adult and pediatric sputnik left ventricular assist devices during mock circulation support. *Cardiol Res Pract*. 2019 Nov 15; 2019: 4593174. doi: 10.1155/2019/4593174.
9. *Itkin GP, Nosov MS, Kuleshov AP, Drobyshev AA, Buchnev AS*. Blood flow control device in implantable extracorporeal circulation systems. Patent for a utility model. No. RU 201911 U1. Patent holder: Shumakov National Medical Research Center of Transplantology and Artificial Organs. 2020.
10. *Syrbu AI, Itkin GP, Kuleshov AP, Gaidai NA*. A mathematical model of neurohumoral regulation of the circulatory system. *Biomedical Engineering*. 2021; 55 (4): 41–44.
11. *Itkin GP, Syrbu AI, Kyleshov AP, Buchnev AS, Drobyshev AA*. Evaluation of the efficiency of a new pulsatile flow-generating circulatory-assist system in rotary blood pumps. Research on a mathematical model. *Russian Journal of Transplantology and Artificial Organs*. 2021; 23 (4): 73–78. (In Russ.). https://doi.org/10.15825/1995-1191-2021-4-73-78.
12. *Cappon F, Wu T, Papaioannou T, Du X, Hsu PL, Khir AW*. Mock circulatory loops used for testing cardiac assist devices: A review of computational and experimental models. *Int J Artif Organs*. 2021 Nov; 44 (11): 793–806. doi: 10.1177/03913988211045405.
13. *Gregory SD, Pauls JP, Wu EL, Stephens A, Steinseifer U, Tansley G, Fraser JF*. An advanced mock circulation loop for *in vitro* cardiovascular device evaluation. *Artif organs*. 2020 Jun; 44 (6): E238–E250. doi: 10.1111/aor.13636.
14. *Rapp ES, Pawar SR, Longoria RG*. Hybrid mock circulatory loop simulation of extreme cardiac events. *IEEE Trans Biomed Eng*. 2022 Sep; 69 (9): 2883–2892. doi: 10.1109/TBME.2022.3156963.
15. *Ochsner G, Amacher R, Amstutz A, Plass A, Daners MS, Tevaearai H et al*. A novel interface for hybrid mock circulations to evaluate ventricular assist devices. *IEEE Trans Biomed Eng*. 2013 Feb; 60 (2): 507–516. doi: 10.1109/TBME.2012.2230000. Epub 2012 Nov 27.
16. *Petrou A, Granegger M, Meboldt M, Daners MS*. A versatile hybrid mock circulation for hydraulic investigations of active and passive cardiovascular implants. *ASAIO J*. 2019 Jul; 65 (5): 495–502. doi: 10.1097/MAT.0000000000000851.
17. *Ślęzak M, Kopernik M, Szawiraacz K, Milewski G*. Assessment of blood flow parameters in a hybrid-digital model of the cardiovascular system applying recurrent neural networks. *Biomedical Signal Processing and Control*. 2024 Dec; 98: 106680. https://doi.org/10.1016/j.bspc.2024.106680.
18. *Syrbu AI, Itkin GP*. Optimization of the parameters of ventricular assist devices using computerized mathematical modeling of the cardiovascular system. *Biomedical Engineering*. 2022; 56 (2): 23–26.
19. *Jansen-Park SH, Mahmood MN, Müller I, Turnhoff LK, Schmitz-Rode T, Steinseifer U, Sonntag SJ*. Effects of interaction between ventricular assist device assistance and autoregulated mock circulation including Frank–Starling mechanism and baroreflex. *Artif Organs*. 2016 Oct; 40 (10): 981–991. doi: 10.1111/aor.12635.

The article was submitted to the journal on 25.07.2025