УДК 616-05.001.575
DOI: 10.24061/3083-5887.j.nmsmme.2024.1.II.2

Model of the cardiovascular system for blood circulation regulation with control elements

Anatoliy Kulyk[1]
: 0000-0003-2472-1665 @: kulyk@vnmu.edu.ua
Oleksandr Vasilevskyi[2]
: 0000-0002-8618-0377 @: oleksandr.vasilevskyi@austin.utexas.edu
Aleksandr Nikolskyy[1]
: 0000-0002-0098-0606 @: alnikolskyy@gmail.com
Viktor Revenok[1]
: 0000-0002-8239-6955 @: vrevenok@ukr.net
Volodymyr Motygin[1]
: 0000-0002-2494-1716 @: **vmotygin@gmail.com**

[1]*National Pirogov Memorial Medical University, Vinnytsya, Ukraine*
[2]*The University of Texas at Austin, USA*

Keywords:
cardiovascular system model;
Kolmogorov-Arnold Networks (KANs);
regulatory and control elements

Abstract

An analysis of existing cardiovascular system models with regulatory loops used for research purposes and disease diagnosis in medicine has been conducted. A dynamic model of the cardiovascular system that accounts for regulatory processes is proposed. The model incorporates one of the key aspects of blood circulation regulation—neural regulation—achieved through the sympathetic and parasympathetic nervous systems. The sympathetic nervous system stimulates the heart to increase the rate and strength of contractions and causes the constriction of peripheral vessels, thereby raising blood pressure. Conversely, the parasympathetic nervous system decreases the heart rate and promotes vessel dilation, lowering blood pressure. These mechanisms interact closely to maintain stable blood circulation in response to the organism's changing physiological needs. Humoral regulation includes the action of various hormones and bioactive substances circulating in the blood that affect the cardiovascular system, which is also considered in the model. The dynamic component of the regulatory system at the intermediate level (humoral system) in the model simulates the formation of mediators, such as adrenaline and noradrenaline,

Cite as:
Kulyk A, Vasilevskyi O, Nikolskyy A, Revenok V, Motygin V. Model of the cardiovascular system for blood circulation regulation with control elements Natural & Mathematical Sciences in Medicine and Medical Education 1(1) 2024 39-48 DOI: 10.24061/3083-5887.j.nmsmme.2024.1.II.2

which travel through the blood vessels. The effects of hormones from the intermediate level on the cardiovascular system are sensed by receptors, such as baroreceptors and chemoreceptors, located in the aorta and the pulmonary circulation, among other places. To enhance the model's functionality, the intermediate regulatory level of the humoral system incorporates a Kolmogorov-Arnold Networks (KANs) system. The KAN network is trained on a knowledge base derived from dozens of acute critical cardiovascular situations. This model can subsequently be used for computer-based prediction and diagnosis of patient diseases and for training medical students.

Модель серцево-судинної системи регулювання кровообігу з елементами керування

Анатолій Кулик[1]
: [0000-0003-2472-1665](https://orcid.org/0000-0003-2472-1665) @: kulyk@vnmu.edu.ua
Олександр Василевський[2]
: [0000-0002-8618-0377](https://orcid.org/0000-0002-8618-0377) @: oleksandr.vasilevskyi@austin.utexas.edu
Олександр Нікольський[1]
: [0000-0002-0098-0606](https://orcid.org/0000-0002-0098-0606) @: alnikolskyy@gmail.com
Віктор Ревенок[1]
: [0000-0002-8239-6955](https://orcid.org/0000-0002-8239-6955) @: vrevenok@ukr.net
Володимир Мотигін[1]
: [0000-0002-2494-1716](https://orcid.org/0000-0002-2494-1716) @: **vmotygin@gmail.com**

[1]*Вінницький національний медичний університет ім. М.І. Пирогова*
[2]*The University of Texas at Austin, USA*

Ключові слова:
модель серцево-судинної системи;
мережа Kolmogorov-Arnold Networks (KANs);
елементи регуляції та керування

Анотація

Проведено аналіз існуючих моделей серцево-судинної системи з контурами регуляції, які використовуються для дослідних цілей та діагностики захворювань у медицині. Запропоновано динамічну модель серцево-судинної системи, яка враховує процеси регуляції. В моделі використано один з ключових аспектів регулювання кровообігу - нервова регуляція, яка здійснюється через симпатичну та парасимпатичну нервові системи. Симпатична нервова система стимулює серце до збільшення частоти скорочень та сили серцевих ударів, а також звуження периферичних судин, що підвищує артеріальний тиск. Парасимпатична нервова система, навпаки, знижує частоту серцевих скорочень і сприяє розширенню судин, знижуючи тиск. Ці механізми діють у тісній взаємодії для підтримання стабільного кровообігу у відповідь на змінні фізіологічні потреби організму. Гуморальна регуляція включає в себе дію різних гормонів та біоактивних речовин, які циркулюють у крові та впливають на серцево-судинну систему, що також враховано в моделі. Динамічна ланка системи регулювання на проміжному рівні (гуморальна система) в моделі імітує утворення медіаторів, наприклад, адреналіну і норадреналіну, які переміщуються з кров'ю по судинам. Результат дії гормонів з проміжного рівня на серцево-судинну систему формується сенсорами, які являють собою, наприклад, баро-, хемо-рецептори, розташовані в аорті, середовищі малого кола і т.п. Для покращення функціональності моделі в проміжний рівень регуляції гуморальної системи введена мережа Kolmogorov-Arnold Networks (KANs). Мережу KAN навчають на базі знань навчальної вибірки з десятків гострих критичних ситуацій серцево-судинної *системи. В подальшому таку модель можна використовувати для комп'ютерного прогнозування та розпізнавання захворювання пацієнтів та для навчання студентів медиків.*

Зміст

Introduction

Since the 1970s, one of the trends in the development of medicine has been the application of mathematical models and methods for the diagnosis and treatment of patients. In our country, this direction began to develop successfully in the 1980s and 1990s by one of the renowned schools led by Academician Mykola Mykhailovych Amosov. This approach has proven promising due to the development of science at the intersection of mathematics, medicine, and engineering [1, 2]. The capabilities of this field have allowed for the determination and comparison of quantitative characteristics of biological systems, identification of inherent causes of complications, development of methods for disease diagnosis, and management of anesthesia in patients during and after heart and vascular surgeries. A technology for individualized therapy, optimal for each patient, was developed, tested in experiments, and implemented in clinical practice.

The early work of the Department of Biocybernetics at the Institute of Cybernetics of the Academy of Sciences of the Ukrainian SSR was associated with modeling various metabolic processes at the cellular and organismal levels. In the mid-1960s, German and American scientists proposed mathematical models of certain physiological processes such as respiration, circulation, and thermoregulation. However, there were few such models, and the approaches to their development and methods of implementation were diverse [3]. A mathematical model of the cell's biochemical processes was also proposed. Due to the complexity of cellular metabolism and the imperfection of computational technology, this model included only some of the most important chains of biochemical reactions, specifically ATP synthesis, some amino acids, nucleic acids, etc. [4].

To create a model of the human organism as a whole, it was necessary to model the systems that ensure its vital activity. From 1968 to 1975, a team of employees from the Department of Biocybernetics at the Institute of Cybernetics of the Ukrainian SSR, led by Mykola Mykhailovych Amosov, worked on creating a mathematical description and digital models of several crucial systems of the organism and studying some of their self-regulatory processes. This included developing a comprehensive model of interconnected physiological systems and using it to study the regulation of vital functions of the organism under normal conditions, and applying the model to reproduce simplified pathological situations.

Digital models of subsystems of some physiological systems of the so-called internal sphere of the organism were also developed: circulation, external respiration and tissue metabolism, water-salt balance, thermoregulation. The work was carried out in three stages: the construction of mathematical models, the study of digital models of individual physiological systems

DOI: 10.24061/3083-5887.j.nmsmme.2024.1.II.2

and processes, and the examination of a complex of digital models of interconnected physiological systems of the human body.

This resulted in the creation of a comprehensive model for the regulation of vital functions of the human body under normal conditions. Research on these models demonstrated that theoretical data aligned well with experimental data. The material obtained could be used both for quantitative analysis of experimental and clinical data and for the systemic analysis of physiological functions. Using the created mathematical model, scientists investigated the regulatory processes of physiological functions under normal body conditions when simulating physical exertion.

The results allowed them to conclude that most of the model's reactions corresponded to experimental data. The proposed complex model of interconnected physiological systems of the human body could also be used to study the role of factors characterizing the adaptation process to physical exertion. This information is particularly important for applications in labor physiology and sports. Additionally, the model was used to study the regulation of physiological functions under conditions of heart pathology, specifically heart failure. The developed model proved to be suitable for reproducing certain pathological states of the human body [5].

For an extended period, artificial reproduction of various diseases and pathological conditions in animal experiments has been widely used in medicine. The realization that the human body can function in conjunction with technical systems led to the emergence of biotechnical systems. One direction of their development was the creation of systems to compensate for lost physiological functions of the body—vegetative, sensory, and motor. Another direction was the development of systems to support the physiological functions of the human body in extreme environmental conditions [5].

The advancement of cybernetics, electronic computing technology, and informatics enabled mathematical modeling of various functional disorders, pathological conditions and processes, and specific diseases and their complications. At the initial stage, cybernetic methods found the most extensive application in physiology, exemplified by obtaining important characteristics of organs and systems.

The most general is the dynamic characteristic, which reflects the change in functions over time under different load conditions. A static characteristic can be obtained in a stationary mode when transitioning from one stable level to another [6].

The development of instrumental base allowed for the registration of many functions and the processing of large amounts of research results. As a result, it became possible to obtain data for quantitative models of algorithmic or structural types. In the first case, a scheme of disease development can be drawn, and an algorithmic description of the model with corresponding digital matrices can be created, followed by probabilistic calculations of the dynamics of the patient's pathological process.

In the second case, during a model experiment, pathological characteristics of organs were obtained, which could be used to predict the disease progression using network structural models. However, there were certain difficulties in creating models. Machine modeling could not compensate for the lack of knowledge about the essence of phenomena that could not be investigated at the time the model was created.

Quantitative characteristics of even well-studied organs were lacking. Additionally, obtaining pathological characteristics of organs and systems was challenging as model experiments took a long time and were difficult to replicate. Despite these difficulties, the first object chosen for the application of quantitative modeling methods in physiology was the heart, as it is one of the most important human organs and can function in isolation.

The fact that M.M. Amosov, who led the work, was a cardiac surgeon also played a significant role. However, the variety of factors affecting heart activity complicated the creation of a complete model of its function.

Therefore, the research was conducted on the heart-lung preparation and was limited to the types of characteristics of heart activity. As a result, the issue of unambiguous quantitative description of heart function under clearly defined conditions was resolved. Additionally, new properties of the mathematical model of the myocardial self-regulation system were demonstrated [6].

At the core of cardiovascular system modeling technology were hemodynamic models that represented the pulsating heart (left and right ventricles, atria, and vascular network), self-regulation of the heart, blood vessels, and circulating blood volume, as well as the humoral background (natural and induced by the administration of dopamine, adrenaline, other medications, and fluids). As a result, significant reductions in complications, mortality, and improvements in therapy quality were achieved [7].

Abroad, the development of cardiovascular system models followed a somewhat different path. Electrical and physico-technical analogs were widely used. In this context, let's consider the most well-known models of blood circulation. The study [8] describes the Windkessel model with lumped parameters, which serves as the foundation for a whole family of zero-dimensional models. Despite the simplicity of such models and the lack of descriptions of regulatory mechanisms, attempts are made to use them to assess various hemodynamic parameters [9]. Many models are built based on hydraulic or electrical analogies [10–12].

The aim of the study is to create a model of the cardiovascular system for blood circulation regulation with control elements.

Model of blood circulation regulation in the cardiovascular system

The cardiovascular system plays a key role in supplying the body with essential nutrients and oxygen, as well as in removing metabolic wastes. The importance of this system for maintaining the body's homeostasis cannot be overstated. The main components of the cardiovascular system are the heart, blood vessels, and blood, which work synchronously to maintain circulation. The regulation of blood circulation is carried out through a complex set of mechanisms that include nervous, humoral, and local regulatory pathways [13].

One of the key aspects of circulation regulation is nervous regulation, which is carried out through the sympathetic and parasympathetic nervous systems. The sympathetic nervous system stimulates the heart to increase the heart rate and the force of cardiac contractions, as well as constrict peripheral vessels, which raises blood pressure. The parasympathetic nervous system, on the other hand, decreases the heart rate and promotes vasodilation, lowering blood pressure. These mechanisms work in close interaction to maintain stable blood circulation in response to the body's changing physiological needs. [14].

Humoral regulation involves the action of various hormones and bioactive substances that circulate in the blood and affect the cardiovascular system. For example, the renin-angiotensin-aldosterone system (RAAS) plays a key role in regulating blood volume and arterial pressure. Angiotensin II, the main hormone of this system, causes vasoconstriction and stimulates the release of aldosterone, which promotes sodium and water retention, thereby increasing blood pressure. [15].

Local regulatory mechanisms include endothelial factors such as nitric oxide (NO) and endothelin-1. NO is a potent vasodilator that reduces vascular tone and promotes vessel dilation, improving blood flow. Endothelin-1, on the contrary, contributes to vasoconstriction and may increase arterial pressure [16].

Regulation of blood circulation also involves the integration of various signals and feedback mechanisms that provide adaptive responses to physical exertion, stressful situations, and other external influences. For instance, during physical

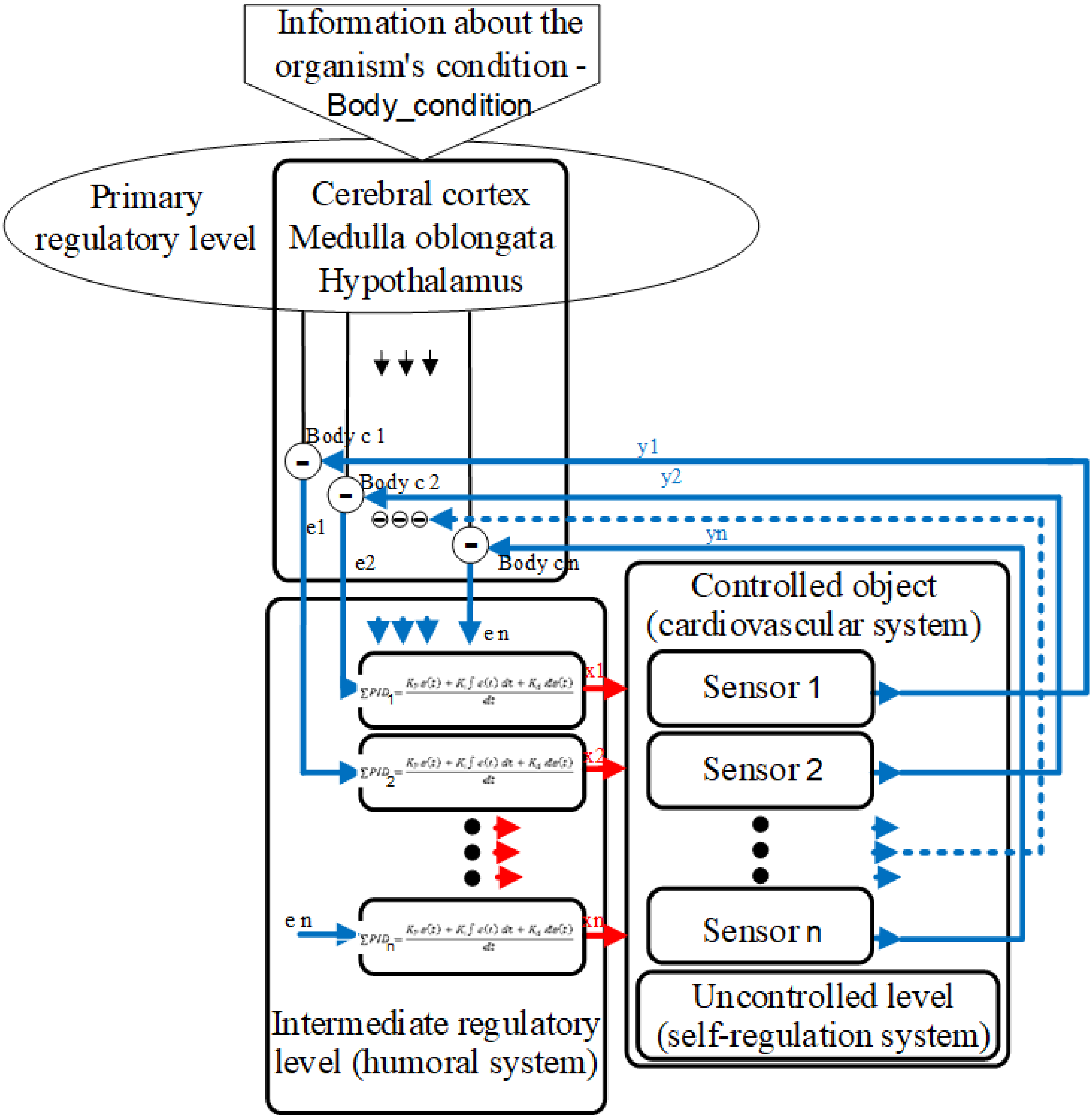

Figure 1 – Structural model of cardiovascular system regulation using control elements (Signals traveling along blood vessels are marked in red, signals traveling along nerve fibers are marked in blue)

exertion, there is an increased demand for oxygen, leading to an elevation in cardiac output and redirection of blood flow to the working muscles [17].

Thus, the comprehensive regulation of blood circulation within the cardiovascular system encompasses numerous mechanisms operating at various levels of organization to ensure the adequate supply of essential substances to organs and tissues. Further research into these mechanisms is crucial for developing new therapeutic approaches to treating cardiovascular diseases.

Modeling the regulatory processes of the cardiovascular system is valuable from a control theory perspective, as it

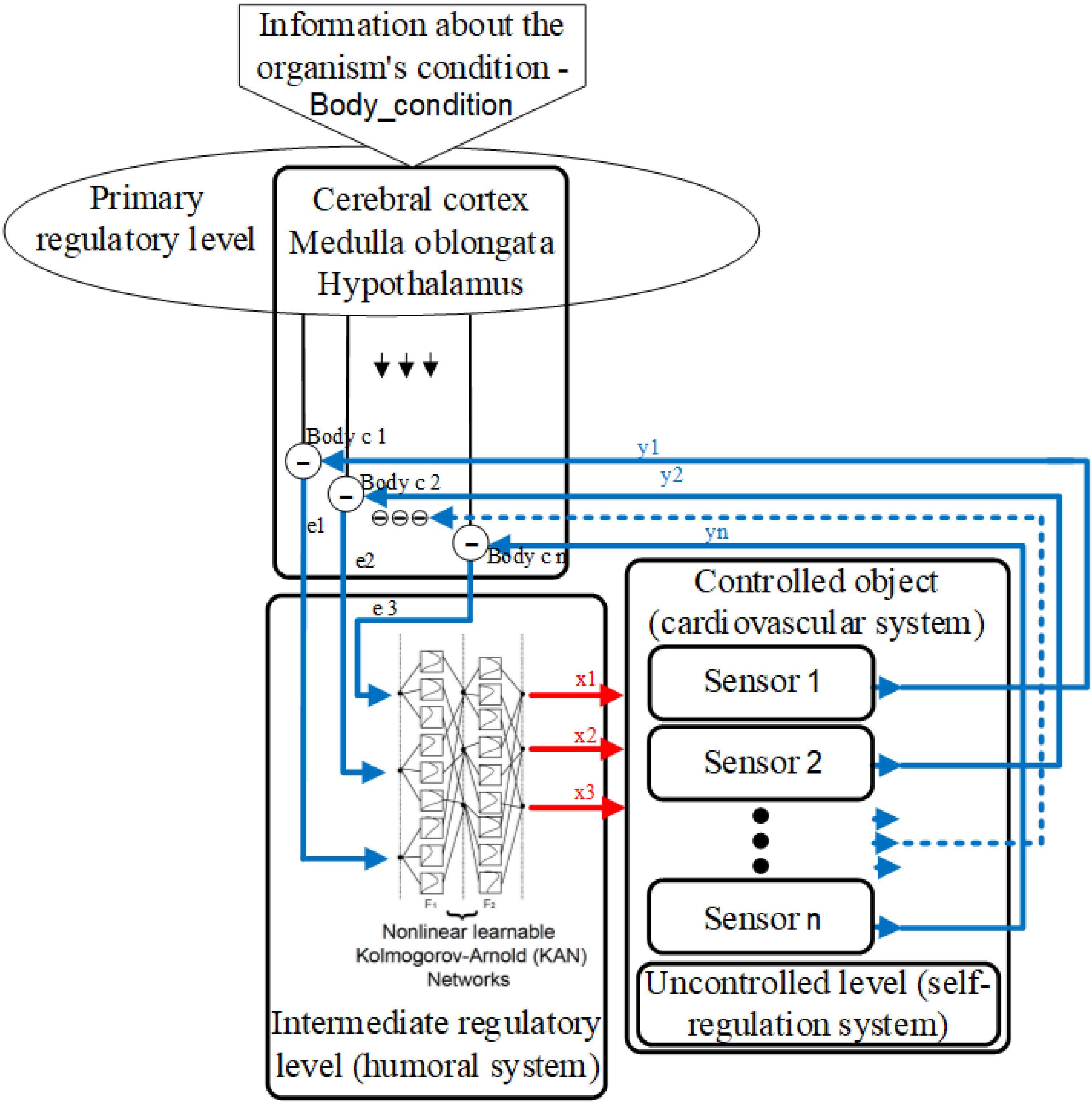

Figure 2 – Structural model of cardiovascular system regulation using Kolmogorov-Arnold Networks (KANs) (Signals traveling along blood vessels are marked in red, signals traveling along nerve fibers are marked in blue)

enables researchers and clinicians to better understand and predict the behavior of this complex system under various conditions. The use of mathematical models and computer simulations allows for the study of cardiovascular system responses to different physiological and pathological stimuli, which would be difficult or impossible to accomplish in vivo.

The proposed model for regulating the cardiovascular system (Fig. 1) consists of the primary level, the intermediate level, and the control object—the cardiovascular system. Within the control object, there is also a local self-regulation system, which represents an uncontrolled level of regulation relative to the primary level.

Nerve signals e1...en, generated at the primary level as the difference between signals indicating the organism's condition (Body_condition, Body c_1...Body c_n) and signals y_1...y_n from the control object, are transmitted to the intermediate level. In the model, a proportional-integral-derivative (PID) control law [18] is used to regulate these signals—this is the simplest algorithm for the functioning of an automatic regulator ∑PID, defined by the following formula:

$$\sum PID = \frac{K_P e(t) + K_i \int e(t)\,dt + K_d\, de(t)}{dt},$$

where Kp, Ki, and Kd are the proportional, integral, and derivative coefficients, respectively.

The dynamic element ∑PID at the intermediate level (humoral system) simulates the formation of mediators x1...xn, such as adrenaline and noradrenaline, which are transported through the blood vessels. The effect of hormones from the intermediate level on the cardiovascular system is sensed by receptors, such as baroreceptors and chemoreceptors, located in the aorta, pulmonary circulation, etc.

Another version of the cardiovascular system regulation model is presented in Fig.2. The intermediate regulatory level of the humoral system incorporates Kolmogorov-Arnold Networks (KANs) [19] as a promising alternative to Multi-Layer Perceptrons (MLP) neural networks. While MLPs have fixed activation functions at the nodes ("neurons"), KANs feature activation functions that can be trained on the edges ("weights"). KANs do not have linear weights at all—each weight parameter is replaced by a one-dimensional function parameterized as a spline. These differences in KANs lead to advantages over MLPs in terms of accuracy and interpretability. In terms of accuracy, much smaller KANs can achieve comparable or better accuracy than much larger MLPs. In this model, the KAN network is trained on a knowledge base derived from dozens of acute critical cardiovascular situations. Such a model can subsequently be used for computer-based prediction and diagnosis of patient diseases as well as for training medical students.

Conclusion

A promising direction in the diagnosis and computer-based prediction of diseases involves the creation of models that enable the assessment of the state and pathological processes of the cardiovascular system. This approach allows for the prediction of blood circulation status resulting from therapeutic interventions and manipulations without harming the patient. Additionally, such a simulator can be used for educational purposes in medical institutions. The further development of these cardiovascular system models could lead to the creation of a medical simulator in the NI LabVIEW software environment [20]. Biomedical engineering is one of the fastest-evolving fields in engineering today. LabVIEW, a graphical programming tool from National Instruments, has been used across multiple classes to teach bioinstrumentation, circuit design, biological signal processing, and image processing concepts in biomedical engineering. Moreover, to increase the functionality of the cardiovascular system regulation model, it is planned to integrate Kolmogorov-Arnold Networks (KANs) into its structure. This can simulate, for instance, several dozen cardiac states. Such a model can subsequently be used for computer-based prediction and diagnosis of patient diseases and for training medical students.

Conflict of interest:
The authors report no conflict of interest.

References

1. Amosov NM, Lyssova OY, Palets BL, Berehovskyi BF. Rehuliatsyia krovoobrashchenyia. Eksperymentalnye y matematycheskye yssledovanyia. Kyev: Naukova dumka; 1977. 157 s.
2. Amosov NM, Lyshchuk VA, Patskyna SA. Samorehuliatsyia serdtsa. Kyev: Naukova dumka; 1969. 157 s.
3. Amosov MM, Lishchuk VO, Palets BL ta inshi. Modeliuvannia «vnutrishnoi sfery» orhanizmu. Fiziol. zhurn. 1971;17(2):156-66.
4. Amosov NM, Ostapov YuH [Matematycheskoe modelyrovanye metabolyzma kletky. Problemy kybernetyky.]. 1972. Zberihaietsia u: IA NBUV NAN Ukrainy. Kyiv; 52, Op. 1., Od. zb. 79., Ark. 1–4.
5. Amosov NM, Palets BL, Ahapov BT y dr. Teoretycheskye yssledovanyia fyzyolohycheskykh system. Matematycheskoe modelyrovanye:. Kyev: Naukova dumka; 1977. 246 s.
6. Amosov NM, Lyshchuk VA, Patskyna SA y dr. Samorehuliatsyia serdtsa. Kyev: Naukova dumka; 1969. 159s
7. Burakovskyi VY, Lyshchuk VA. Rezultaty indyvidualnoi dyahnostyky i terapiyi boln'ykh ostrymy rasstroistvamy krovoobrashchenyia (na osnove matematycheskykh modelei). Kyev: AN USSR; 1985. 53s.
8. Shi Y, Lawford P, Hose R. Review of Zero-D and 1-D Models of Blood Flow in the Cardiovascular System. Biomed Eng OnLine [Інтернет]. 2011 [цитовано 20 трав. 2024];10(1):33. Доступно на: https://doi.org/10.1186/1475-925x-10-33
9. Her K, Kim JY, Lim KM, Choi SW. Windkessel model of hemodynamic state supported by a pulsatile ventricular assist device in premature ventricle contraction. Biomed Eng OnLine [Інтернет]. 2 лют. 2018 [цитовано 20 трав. 2024];17(1). Доступно на: https://doi.org/10.1186/s12938-018-0440-5
10. Ribarič S, Kordaš M. Teaching cardiovascular physiology with equivalent electronic circuits in a practically oriented teaching module. Adv Physiol Educ [Інтернет]. Черв. 2011 [цитовано 20 трав. 2024];35(2):149-60. Доступно на: https://doi.org/10.1152/advan.00072.2010
11. de Canete JF, Saz-Orozco PD, Moreno-Boza D, Duran-Venegas E. Object-oriented modeling and simulation of the closed loop cardiovascular system by using SIMSCAPE. Comput Biol Med [Інтернет]. Трав. 2013 [цитовано 20 трав. 2024];43(4):323-33. Доступно на: https://doi.org/10.1016/j.compbiomed.2013.01.007
12. Ribarič S, Kordaš M. Simulation of the Frank-Starling Law of the Heart. Comput Math Methods Med [Інтернет]. 2012 [цитовано 20 трав. 2024];2012:1-12. Доступно на: https://doi.org/10.1155/2012/267834
13. Shevchuk VH, Moroz VM, Biela SM, ta in. Fiziolohiia: pidruchnyk dlia stud. vyshch. med. navch. zakladiv. Vinnytsia: Nova knyha; 2012. 448 s.[in Ukrainian]
14. Guyton AC, Hall JE. Textbook of Medical Physiology. Elsevier; 2021. 1091 p.
15. Klabunde RE. Cardiovascular Physiology Concepts. 2nd ed. Lippincott Williams & Wilkins; 2011. 235 p.
16. Feletou M, Vanhoutte PM . Endothelial dysfunction: A multifaceted disorder. Am J Physiol Heart Circ Physiol. 2006;291(3):985-1002.
17. Rowell LB. Human Cardiovascular Control. Oxford University Press; 1993. 500 p.
18. Uchasnyky proektiv Vikimedia. Vikipediia [Internet]. Proportsiino-intehralno-dyferentsialnyi zakon rehuliuvannia — Vikipediia; 23 berez. 2011 [tsytovano 20 trav. 2024]. Available at: https://uk.wikipedia.org/wiki/Пропорційно-інтегрально-диференціальний_закон_регулювання
19. Liu Z, Wang Y, Vaidya S, Ruehle F, Halverson J, Soljačić M, et al. KAN: Kolmogorov-Arnold Networks [Internet]. arXiv; 2024. Available from: https://arxiv.org/abs/2404.19756
20. Mess- und Prüfsysteme, bei Emerson - NI [Інтернет]. What is NI LabVIEW? Graphical Programming for Test & Measurement; [цитовано 20 трав. 2024]. Доступно на: https://www.ni.com/en/shop/labview.html?srsltid=AfmBOop46A9HLxGGgrFzm-84J3_x0kBe9O2d_V7HiqjLBaUcdLYZeMou

Список використаних джерел

1 Амосов НМ, Лиссова ОИ, Палец БЛ, Береговский БФ. Регуляция кровообращения. Эксперимен-

тальные и математические исследования. Киев: Наукова думка; 1977. 157 с.
2. Амосов НМ, Лищук ВА, Пацкина СА. Саморегуляция сердца. Киев: Наукова думка; 1969. 157 с.
3. Амосов ММ, Ліщук ВО, Палець БЛ та інші. Моделювання «внутрішньої сфери» організму. Фізіол. журн. 1971;17(2):156-66.
4. Амосов НМ, Остапов ЮГ [Математическое моделирование метаболизма клетки. Проблемы кибернетики.]. 1972. Зберігається у: ІА НБУВ НАН України. Київ; 52, Оп. 1., Од. зб. 79., Арк. 1–4.
5. Амосов НМ, Палец БЛ, Агапов БТ и др. Теоретические исследования физиологических систем. Математическое моделирование:. Киев: Наукова думка; 1977. 246 с.
6. Амосов НМ, Лищук ВА, Пацкина СА и др. Саморегуляция сердца. Киев: Наукова думка; 1969. 159 с
7. Бураковский ВИ, Лищук ВА. Результаты индивидуальной диагностики и терапии больных острыми расстройствами кровообращения (на основе математических моделей). Киев: АН УССР; 1985. 53 с.
8. Shi Y, Lawford P, Hose R. Review of Zero-D and 1-D Models of Blood Flow in the Cardiovascular System. Biomed Eng OnLine [Інтернет]. 2011 [цитовано 20 трав. 2024];10(1):33. Доступно на: https://doi.org/10.1186/1475-925x-10-33
9. Her K, Kim JY, Lim KM, Choi SW. Windkessel model of hemodynamic state supported by a pulsatile ventricular assist device in premature ventricle contraction. Biomed Eng OnLine [Інтернет]. 2 лют. 2018 [цитовано 20 трав. 2024];17(1). Доступно на: https://doi.org/10.1186/s12938-018-0440-5
10. Ribarič S, Kordaš M. Teaching cardiovascular physiology with equivalent electronic circuits in a practically oriented teaching module. Adv Physiol Educ [Інтернет]. Черв. 2011 [цитовано 20 трав. 2024];35(2):149-60. Доступно на: https://doi.org/10.1152/advan.00072.2010
11. de Canete JF, Saz-Orozco PD, Moreno-Boza D, Duran-Venegas E. Object-oriented modeling and simulation of the closed loop cardiovascular system by using SIMSCAPE. Comput Biol Med [Інтернет]. Трав. 2013 [цитовано 20 трав. 2024];43(4):323-33. Доступно на: https://doi.org/10.1016/j.compbiomed.2013.01.007
12. Ribarič S, Kordaš M. Simulation of the Frank-Starling Law of the Heart. Comput Math Methods Med [Інтернет]. 2012 [цитовано 20 трав. 2024];2012:1-12. Доступно на: https://doi.org/10.1155/2012/267834
13. Шевчук ВГ, Мороз ВМ, Бєла СМ, та ін. Фізіологія: підручник для студ. вищ. мед. навч. закладів. Вінниця: Нова книга; 2012. 448 с.
14. Guyton AC, Hall JE. Textbook of Medical Physiology. Elsevier; 2021. 1091 p.
15. Klabunde RE. Cardiovascular Physiology Concepts. 2-ге вид. Lippincott Williams & Wilkins; 2011. 235 p.
16. Feletou M, Vanhoutte PM . Endothelial dysfunction: A multifaceted disorder. Am J Physiol Heart Circ Physiol. 2006;291(3):985-1002.
17. Rowell LB. Human Cardiovascular Control. Oxford University Press; 1993. 500 p.
18. Учасники проектів Вікімедіа. Вікіпедія [Інтернет]. Пропорційно-інтегрально-диференціальний закон регулювання — Вікіпедія; 23 берез. 2011 [цитовано 20 трав. 2024]. Доступно на: https://uk.wikipedia.org/wiki/Пропорційно-інтегрально-диференціальний_закон_регулювання
19. Liu Z, Wang Y, Vaidya S, Ruehle F, Halverson J, Soljačić M, et al. KAN: Kolmogorov-Arnold Networks [Internet]. arXiv; 2024. Available from: https://arxiv.org/abs/2404.19756
20. Mess- und Prüfsysteme, bei Emerson - NI [Інтернет]. What is NI LabVIEW? Graphical Programming for Test & Measurement; [цитовано 20 трав. 2024]. Доступно на: https://www.ni.com/en/shop/labview.html?srsltid=AfmBOop46A9HLxGGgrFzm-84J3_x0kBe9O2d_V7HiqjLBaUcdLYZeMou