

Pediatric cardiovascular surgery in Russia: from fundamental barriers to high-tech solutions

Ruben R. Movsesyan^{1,2}, Ilya A. Soynov^{1,3}

Corresponding author: Ilya A. Soynov,
i_soynov@meshalkin.ru

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¹ Interregional Public Organization of Pediatric Cardiac Surgeons "Society of Congenital Heart Disease Specialists", St. Petersburg, Russian Federation

² Children's City Multidisciplinary Clinical Specialized Center for High Medical Technologies, St. Petersburg, Russian Federation

³ Meshalkin National Medical Research Center, Novosibirsk, Russian Federation

Abstract

Introduction: Pediatric cardiovascular surgery in Russia is undergoing a major transformation. Along with further reduction in mortality, increasing emphasis is being placed on long-term quality of life, reduction of disability, personalized treatment, and continuity of care for patients with congenital heart disease.

Objective: To systematize the key scientific and clinical directions, fundamental barriers, and promising technological solutions in the development of pediatric cardiovascular surgery in Russia.

Materials: This study was designed as an analytical (narrative) review. Recent Russian and international publications were analyzed together with materials reflecting scientific and clinical activities of 27 leading Russian centers participating in a multicenter pediatric cardiovascular surgery initiative. Sources were selected thematically, with emphasis on perinatal cardiology, neonatal surgery, bioengineering, neuroprotection, Fontan circulation, arrhythmology, immunological consequences of cardiac surgery, and organizational models of patient routing and follow-up.

Results: The major barriers identified include the vulnerability of newborns with critical congenital heart disease and extremely low birth weight, the mismatch between a child's growth and the durability of current prosthetic materials, neurocognitive sequelae after cardiopulmonary bypass, long-term complications of Fontan circulation, arrhythmologic problems after congenital heart defect repair, and immune-related risks associated with thymectomy and genetically determined immune dysfunction. Strategic solutions include predictive perinatal diagnostics, improved organ protection, development of domestic bioengineering and transcatheter technologies, 3D modeling and digital twins, establishment of dedicated Fontan centers, expansion of mechanical circulatory support and transplantation programs, and implementation of telemedical monitoring and interdisciplinary rehabilitation.

Conclusion: The development of pediatric cardiovascular surgery in Russia requires integration of clinical, bioengineering, digital, and organizational solutions. The combination of domestic innovations, multicenter collaboration, and national registries may improve

Contribution of the authors

Conception and study design: R.R. Movsesyan

Data collection and analysis: I.A. Soynov

Drafting the article: both authors

Critical revision of the article: I.A. Soynov

Final approval of the version to be published: both authors

ORCID

R.R. Movsesyan, <https://orcid.org/0000-0003-3089-3113>

I.A. Soynov, <https://orcid.org/0000-0003-3691-2848>

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treatment effectiveness, long-term outcomes, and technological independence of the field.

Keywords: bioengineering; congenital heart disease; Fontan circulation; mechanical circulatory support; neuroprotection; pediatric cardiac surgery; transcatheter pulmonary valve

Развитие детской сердечно-сосудистой хирургии в России: от системных барьеров к высокотехнологичным решениям

Р.Р. Мовсесян^{1,2}, И.А. Сойнов^{1,3}

Для корреспонденции: Илья Александрович Сойнов,
i_soynov@meshalkin.ru

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¹ Межрегиональная общественная организация детских кардиохирургов «Общество специалистов по врожденным порокам сердца», Санкт-Петербург, Российская Федерация

² Санкт-Петербургское государственное бюджетное учреждение здравоохранения «Детский городской многопрофильный клинический специализированный центр высоких медицинских технологий», Санкт-Петербург, Российская Федерация

³ Федеральное государственное бюджетное учреждение «Национальный медицинский исследовательский центр имени академика Е.Н. Мешалкина» Министерства здравоохранения Российской Федерации, Новосибирск, Российская Федерация

Аннотация

Актуальность. Детская сердечно-сосудистая хирургия в России переживает этап качественной трансформации: при сохраняющемся приоритете снижения летальности все большее значение приобретают долгосрочное качество жизни, снижение инвалидизации, персонализация лечения и преемственность ведения пациентов с врожденными пороками сердца.

Цель. Систематизировать ключевые научно-практические направления, фундаментальные барьеры и перспективные технологические решения в развитии детской сердечно-сосудистой хирургии в России.

Материалы. Работа выполнена как аналитический (нарративный) обзор. Проанализированы современные отечественные и зарубежные публикации, а также материалы, отражающие научно-практические направления 27 ведущих российских клиник, участвующих в проекте межцентрового взаимодействия в области сердечно-со-

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Вклад авторов

Концепция и дизайн работы: Р.Р. Мовсесян
Сбор и анализ данных: И.А. Соинов
Написание статьи: оба автора
Исправление статьи: И.А. Соинов
Утверждение окончательного варианта статьи: оба автора

ORCID

Р.Р. Мовсесян,

<https://orcid.org/0000-0003-3089-3113>

И.А. Соинов, <https://orcid.org/0000-0003-3691-2848>

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судистой хирургии у детей. Отбор источников проводили по тематическому принципу с акцентом на перинатальную кардиологию, хирургию новорожденных, биоинженерию, нейропротекцию, гемодинамику Фонтена, аритмологию, иммунологические последствия кардиохирургических вмешательств и организационные модели маршрутизации и наблюдения пациентов.

Результаты. Выделены ключевые барьеры развития отрасли: высокая уязвимость новорожденных с критическими пороками сердца и экстремально низкой массой тела, несоответствие между ростом ребенка и сроком службы существующих протезов, нейрокогнитивные нарушения после операций с искусственным кровообращением, отдаленные осложнения циркуляции Фонтена, аритмологические проблемы у пациентов после коррекции врожденных пороков сердца, а также иммунологические риски, связанные с тимусэктомией и генетически детерминированными иммунными нарушениями. В качестве стратегических решений рассматриваются предиктивная перинатальная диагностика, совершенствование органопротекции, развитие отечественной биоинженерии и транскатетерных технологий, применение 3D-моделирования и цифровых двойников, создание специализированных Фонтен-центров, расширение программ механической поддержки кровообращения и трансплантации, а также развитие телемедицинского мониторинга и междисциплинарной реабилитации.

Заключение. Развитие детской сердечно-сосудистой хирургии в России требует интеграции клинических, биоинженерных, цифровых и организационных решений. Сочетание отечественных разработок, межцентрового сотрудничества и данных национальных регистров способно повысить эффективность лечения, улучшить отдаленные исходы и укрепить технологическую самостоятельность отрасли.

Ключевые слова: биоинженерия; врожденные пороки сердца; гемодинамика Фонтена; детская кардиохирургия; механическая поддержка кровообращения; нейропротекция; транскатетерный клапан легочной артерии



Introduction

Modern pediatric cardiovascular surgery in the Russian Federation is undergoing a period of profound qualitative transformation driven not only by refinement of surgical techniques, but also by the active integration of advances in basic science, bioengineering, molecular diagnostics, and digital technologies [1]. In the context of current demographic policy, reduction of infant mortality and disability among children with congenital heart disease (CHD) remains a major national healthcare priority [2]. At the same time, the professional focus is gradually shifting from immediate survival alone toward minimization of surgical trauma, improvement in long-term quality of life, preservation of neurocognitive function, and personalization of therapeutic strategies [3–5]. The

scientific potential of the field is concentrated within national medical research centers and leading regional institutions that are shaping both the research agenda and clinical priorities for the coming years. A distinctive feature of the current stage is the interdisciplinary and multicenter nature of this work, bringing together cardiac surgeons, cardiologists, geneticists, cardiac anesthesiologists and intensivists, clinical immunologists, imaging specialists, rehabilitation physicians, and experts in digital health technologies.

Unlike studies focused on specific procedures or narrowly defined clinical problems, the present analytical review aims to systematize the key scientific and practical directions in the development of pediatric cardiovascular surgery in Russia as a unified clinical, technological, and organizational domain.

Particular attention is given to areas that are shaping the long-term agenda of the field: neonatal surgery, bioengineering, cerebral and end-organ protection, management of patients with Fontan physiology, arrhythmology, immunologic surveillance, and issues of continuity of care and digital patient support [6–11].

The aim of this review was to systematize the key scientific and clinical directions, fundamental barriers, and promising technological solutions in the development of pediatric cardiovascular surgery in Russia.

Brief Overview of the Review Methodology

This work was designed as an analytical narrative review. The analysis was based on contemporary Russian and international publications, as well as materials reflecting the scientific and clinical priorities of 27 leading Russian centers participating in an interinstitutional collaborative project in pediatric cardiovascular surgery. Sources were selected thematically, with emphasis on the most clinically and organizationally relevant areas: critical congenital heart defects in neonates, bioengineered solutions in reconstructive surgery, neuroprotection, management after the Fontan procedure, interventional and surgical arrhythmology, immunologic consequences of cardiac surgical interventions, and models of long-term follow-up. The study was not intended to perform a formal systematic search or meta-analysis, which is consistent with the narrative review format.

System-Level Analysis of the Contemporary Problem Landscape in Pediatric Cardiac Surgery

The current stage of development of pediatric cardiovascular surgery is characterized by the coexistence of major surgical advances and a persistent set of unresolved problems resulting from the increasing complexity of the patient population [12; 13]. Although mortality after CHD repair has steadily declined overall, [14] several fundamental challenges remain and continue to shape both the scientific and organizational agenda of the field.

Surgery for Neonatal Critical Conditions: The “Critical Window” and Biological Vulnerability of the Newborn

Among the central unresolved issues are the high mortality and disability risks in neonates with

critical CHD requiring urgent intervention [6; 7; 11; 15]. The major challenge lies in the extremely narrow therapeutic window, in which surgery must be performed within the first hours or days of life against a background of physiologic immaturity of multiple organ systems [16; 17]. This problem is further compounded by the growing number of preterm infants and neonates with low birth weight (<2500 g) or very low birth weight (1500 g), in whom standard cardiopulmonary bypass protocols and conventional surgical access are associated with a high risk of fatal complications [18; 19].

Despite advances in prenatal diagnosis, it does not always allow accurate prediction of postnatal hemodynamics, adaptive reserve, or the rate of somatic growth. For some complex anatomic forms of CHD, prenatal detection remains limited [20; 21].

This creates uncertainty regarding timing of delivery, referral pathways, and the strategy for the initial stage of surgical care. The mismatch between the severity of the anatomical defect and the newborn’s metabolic reserve underscores the need for less invasive and more tissue-sparing approaches to circulatory stabilization, including endovascular palliation, hybrid techniques, and new organ-protection strategies during cardiopulmonary bypass [22].

The “Growing Heart” Versus the “Ideal Prosthesis”: Biotechnology and Bioengineering in Cardiac Surgery

A fundamental problem in pediatric cardiac surgery is the search for materials capable of functional integration into recipient tissues and, ideally, adaptation to a child’s growth [23; 24]. The use of synthetic conduits and biologic prostheses in children inevitably leads to prosthesis–patient mismatch as the child grows, thereby initiating a cycle of repeat interventions that become progressively more technically demanding and hazardous.

This challenge is aggravated by calcification and degeneration of biologic materials, processes that occur more rapidly in children than in adults because of age-related features of calcium metabolism and heightened immune reactivity [25]. The need for multiple reoperations increases the risks of bleeding, injury to intrathoracic structures during re sternotomy, infectious complications, and psychosocial stress for

the family, while also increasing the burden on the healthcare system [25].

Neurocognitive Deficit and the Systemic Inflammatory Response

Surgery for congenital heart defects is inseparably associated with exposure to the adverse effects of cardiopulmonary bypass [7; 26–28]. The systemic inflammatory response induced by blood contact with foreign surfaces in the extracorporeal circuit, ischemia-reperfusion injury, hypothermia, and hemodilution exerts harmful effects on multiple organs and systems [27]. However, the developing brain remains the most vulnerable target [26; 28].

Neurocognitive impairment after cardiac surgery has therefore emerged as an issue of particular importance. A substantial proportion of patients demonstrate long-term deficits in memory, attention, executive functioning, language, behavior, and emotional regulation [29; 30]. These disorders are multifactorial in origin, involving microembolization, perioperative hypoxia, genetic susceptibility, features of cerebral blood flow, and the staged nature of treatment [29; 30]. Accordingly, traditional criteria of operative safety are no longer sufficient, and prevention of microstructural white-matter injury requires new protocols for

neuroprotection, intraoperative neuromonitoring, and early neuropsychological rehabilitation.

The Single-Ventricle Paradox and Long-Term Consequences of Fontan Hemodynamics

Management of patients with univentricular circulation remains one of the most challenging problems in the field [3]. Although the staged surgical pathway is well established, the Fontan operation is fundamentally palliative and creates a unique physiologic state characterized by passive pulmonary blood flow under chronically elevated central venous pressure [3].

Long-term complications of Fontan hemodynamics include protein-losing enteropathy, plastic bronchitis, chronic heart failure, thromboembolic events, and progressive liver injury known as Fontan-associated liver disease (FALD) [3]. A major difficulty is that many of these complications manifest 15–20 years after surgery, when patients transition into the adult healthcare system, which may not always have sufficient expertise in this population [31]. This underscores the need for integrated long-term care involving cardiology, cardiac surgery, hepatology, arrhythmology, rehabilitation medicine, and transplantation.

Table 1. Barriers and Strategic Solutions in Pediatric Cardiac Surgery

Barrier	Clinical significance	Strategic solution	Promising domestic directions
Neonates with critical CHD and extremely low body weight	High risk of mortality and complications	Predictive diagnostics, referral optimization, organ protection	Integrated perinatal-cardiac surgical centers, selective perfusion
The “growing prosthesis” problem	Need for repeat operations	Bioengineering, transcatheter solutions	Polytetrafluoroethylene valves, decellularized grafts
Neurocognitive deficit	Reduced quality of life	Neuromonitoring, neuroprotection, early rehabilitation	3D modeling, biofeedback therapy
Fontan hemodynamics	Severe late complications	Dedicated Fontan centers	Multidisciplinary follow-up, LVAD
Immunologic complications	Infection, immune dysregulation	Genetic screening, immune monitoring	Personalized prophylaxis

Note. LVAD, left ventricular assist device.

Arrhythmologic Burden

Myocardial scarring after surgical incisions, ventriculotomies, intracardiac patch reconstruction, and chronic chamber overload creates a stable substrate for life-threatening arrhythmias [32]. Of particular clinical concern is the diagnosis and treatment of arrhythmias in young children, especially in patients younger than 6 years and weighing <13 kg [32; 33].

In this age group, standard interventional approaches are limited by anatomic constraints, small vessel caliber, and the high vulnerability of the cardiac conduction system. Radiofrequency ablation and implantation of antiarrhythmic devices require not only a highly experienced team but also specialized ultra-small-caliber instruments [32; 33]. Thus, arrhythmology in children with CHD is emerging as an independent high-technology discipline requiring dedicated organizational infrastructure.

Immunologic Aspects and Genetic Syndromes

Another increasingly important area is the study of immunologic consequences of cardiac surgery [34]. Thymectomy, often performed to improve surgical exposure in neonates and infants, may have long-term consequences for the immune system, including T-cell abnormalities, features of premature immunosenescence, and predisposition to infectious and autoimmune complications [34].

The importance of this problem increases further in patients with genetically determined immune dysfunction, particularly those with DiGeorge syndrome or heterotaxy syndromes, which may be associated with asplenia or polysplenia [35]. The overlap of surgical trauma, systemic inflammatory response, and partial or complete thymectomy with preexisting immune defects markedly increases the risk of severe infectious complications. This necessitates inclusion of both a clinical immunologist and a medical geneticist in the standard multidisciplinary care pathway for such patients.

Organizational Challenges Related to Fragmented Care and Follow-up Coordination

A major limitation to the effectiveness of even high-technology cardiac surgical care is the fragmentation of

patient management after discharge from a specialized center. Parents often face inadequate information, referral difficulties, limited access to specialized care in their home region, and substantial variability in the quality of outpatient follow-up [36].

Administrative fragmentation between inpatient and outpatient services, the absence of unified national standards for rehabilitation and remote monitoring, and limited implementation of digital clinical decision-support systems all constrain development of a continuous model of care. As a result, some of the clinical gains achieved at the stage of high-technology intervention may be lost over the long term.

Strategic Solutions and Innovative Development Vectors in Pediatric Cardiac Surgery

Overcoming these barriers requires a shift from the extensive accumulation of surgical experience to the intensive implementation of science-driven technologies, interdisciplinary models of care, and organizational innovation. Analysis of current trends allows several key development vectors to be identified (Table 1).

Perinatal Cardiology and Neonatal Surgery: Predictive Diagnostics and Referral Pathways

The contemporary strategy of care for children with critical congenital heart defects is based on a preventive approach beginning in the prenatal period [10]. One of the most important tasks is the transition from merely identifying an anatomic defect to predicting the postnatal hemodynamic scenario, surgical risk, and the urgency of intervention [37].

Comprehensive assessment of maternal biophysical and biochemical markers, together with hemodynamic parameters within the mother–placenta–fetus system, may improve prediction of fetal growth, organ maturity, and postnatal stability [38]. Equally important is the organizational solution of concentrating high-risk pregnancies and neonates with critical CHD in integrated perinatal-cardiac surgical centers, where the hazards associated with transport of an unstable infant can be minimized [39].

At the surgical level, organ-protection strategies in children with very low and extremely low birth weight

are of particular importance. Aortic arch reconstruction performed under selective cerebral and coronary perfusion without deep hypothermic circulatory arrest may reduce the severity of ischemic organ injury [40; 41]. At the same time, traditional approaches to anatomically complex defects are being reconsidered, and variants of biventricular repair for severe forms of left heart hypoplasia and critical aortic stenosis are being investigated and partially implemented [9; 42].

Technological Sovereignty Through Biotechnology and Bioengineering

One of the fundamental tasks of contemporary Russian cardiac surgery is to overcome the shortage of materials capable of biologic adaptation in the growing child [23]. This challenge is being addressed through the pursuit of technological sovereignty in the production of valved conduits and next-generation synthetic prostheses [43; 44]. A key direction is the development of domestic balloon-expandable transcatheter prostheses, including a polytetrafluoroethylene-based pulmonary valve [44], as well as self-expanding xenopericardial transcatheter valves with enhanced anti-calcification protection [43]. This technology may substantially reduce the rates of calcification and structural valve degeneration typical of bioprostheses, while also allowing endovascular correction of dysfunction without repeat open surgery [45].

A second important area is the refinement of decellularization protocols for biologic tissues, including xenografts and homografts. Removal of the cellular component reduces material immunogenicity, thereby limiting rapid rejection and degeneration under conditions of highly reactive neonatal immunity [46]. Reconstructive surgery of native valves has also evolved substantially, with widespread adoption of autologous pericardial neovalve construction, including Ozaki-type procedures [47; 48]. However, the surgical community must interpret these techniques with caution. Practical experience indicates that synchronous long-term growth of autopericardial constructs or living homografts together with the physiologic growth of the child's heart does not, in fact, occur [23; 49]. Although such interventions provide excellent early hemodynamics and spare patients

lifelong anticoagulation, recurrent dysfunction—either regurgitation or stenosis—develops over time [47; 48]. This necessitates rigorous echocardiographic surveillance to enable timely planning of the inevitable reoperations at later stages of growth [49].

Precision Diagnostics, Neuroprotection, and Digitalization of Decision-Making

Reducing neurocognitive injury after cardiopulmonary bypass has become one of the most important goals of modern pediatric cardiac surgery [29; 30]. A strategic response is the transition to personalized neuroprotection protocols, including selective antegrade cerebral perfusion, advanced neuromonitoring, and early postoperative rehabilitation [50].

Digitalization has elevated preoperative planning to a new level. The use of 3-dimensional modeling, printed anatomic models, and virtual reality technologies makes it possible to analyze patient-specific anatomy in detail, simulate procedural stages, and reduce cardiopulmonary bypass duration [51; 52]. This approach is especially valuable in rare or anatomically complex forms of CHD.

The formation of multidisciplinary teams involving cardiac surgeons, cardiac anesthesiologists and intensivists, neurologists, specialists in functional diagnostics, and rehabilitation physicians makes it possible not only to ensure surgical survival, but also to improve cognitive and behavioral outcomes in affected children [53].

Management of Univentricular Physiology and Mechanical Circulatory Support

The care of patients with a functionally single ventricle represents one of the most complex logistical and clinical challenges in the field [31]. The Fontan operation creates profoundly nonphysiologic circulation, with entirely passive pulmonary blood flow in the setting of high central venous pressure and low cardiac output [3]. Over time, this leads to potentially catastrophic consequences, including protein-losing enteropathy, plastic bronchitis, and progressive hepatic fibrosis (FALD) [3].

To prevent these outcomes, a strategic priority is the establishment of national Fontan centers—specialized outpatient–inpatient clusters dedicated to lifelong

management of this patient population. The functions of such centers should include regular noninvasive hemodynamic assessment, liver screening, surveillance of the lymphatic system, and coagulation monitoring [3]. Of particular concern is the highly challenging and increasingly relevant issue of pregnancy and delivery in women with Fontan physiology [54], which carries exceptionally high risks of thrombosis, arrhythmia, and fatal decompensation. This area requires development of meticulous consensus protocols for multidisciplinary case conferences involving obstetricians-gynecologists and hematologists.

In situations in which both conservative and surgical options have been exhausted and systolic function of the single ventricle continues to decline, long-term mechanical circulatory support with a left ventricular assist device (LVAD) may become the only viable option [55]. Given the severe shortage of pediatric donor hearts, the integration, adaptation, and miniaturization of LVAD systems in domestic practice offer a chance to save lives by providing a reliable bridge to transplantation – or, in selected cases, destination therapy [56]. Expansion of transplantation programs, including heart transplantation in highly complex combined malformations, complements this algorithm and may provide durable survival when conventional reconstructive surgery has reached its limits [57].

Interventional and Surgical Arrhythmology: Establishing Centers of Functional Expertise

Marked myocardial scarring after ventriculotomies, the use of extensive intracardiac patches, and chronic volume overload create a powerful substrate for unpredictable and life-threatening rhythm disturbances [32]. Standard antiarrhythmic drug therapy in children after CHD repair is often ineffective [32]. A strategic solution is the establishment of dedicated arrhythmology centers within cardiac surgical institutions.

The most challenging subgroup consists of young children (<6 years) weighing <13 kg [58]. Surgery or ablation for arrhythmias in patients of such low body weight is constrained by major anatomic barriers: extremely small intracardiac structures, thin myocardial walls, and a high risk of irreversible injury to the conduction system, particularly atrioventricular

block [58]. Traditional interventional approaches are therefore limited. Progress in this area depends on implementation of advanced hybrid strategies that combine the expertise of the cardiac surgeon, who provides safe access, and the electrophysiologist. Key technologies include high-resolution electroanatomic nonfluoroscopic 3-dimensional mapping systems, focal cryoablation, and robot-assisted catheter navigation systems [33]. Only the combination of such microscale instrumentation and multidisciplinary expertise allows safe elimination of arrhythmogenic foci in the context of distorted and highly atypical postoperative anatomy in the small child's heart.

Personalized Immune Monitoring and Genetic Spectra

For many years, the immunologic consequences of cardiac surgery remained outside the primary focus of surgeons; today, however, they are recognized as a major determinant of survival. Prevention of septic complications begins with understanding the role of the thymus, which is traditionally removed (thymectomy) to provide adequate exposure through median sternotomy [34]. In a neonate, thymus removal implies a substantial reduction in T-lymphocyte maturation, which in turn may lead to premature immune aging and a high risk of severe generalized infections or autoimmune dysregulation [34].

The situation becomes especially critical in the presence of preexisting genetic determinants. For example, in heterotaxy syndromes, severe CHD may coexist anatomically with asplenia or functionally impaired polysplenia, whereas DiGeorge syndrome is associated with primary T-cell deficiency [35]. Superimposition of surgical trauma and thymectomy on a genetically determined defect of lymphoid organs greatly increases the risk of early postoperative death from sepsis. A systems-level response to this challenge includes implementation of preoperative molecular genetic screening and mandatory involvement of clinical immunologists. For this patient population, strictly personalized lifelong programs for infectious and immune surveillance should be developed, supported by expanded targeted vaccination strategies and protocols for prophylactic antibiotic therapy; where technically feasible, surgeons should also aim to preserve part of the thymus [34].

Continuity of Monitoring and Comprehensive Medical-Social Rehabilitation

A successful cardiac surgical procedure is only the first stage in a much longer struggle to preserve life and health. A key organizational problem in contemporary medicine is fragmentation of care after discharge, when a patient leaves a high-technology federal center and returns to a region that may lack the specialized professionals needed for adequate follow-up. Insufficient continuity across stages of treatment undermines part of the achieved benefit and reduces the overall clinical effectiveness of surgical care.

A strategic instrument for addressing this problem is the implementation of digital systems for remote outpatient monitoring, including telemedicine consultations and home transmission of echocardiographic, electrocardiographic, and pulse oximetry data, allowing federal experts to detect early signs of decompensation from a distance [36; 59]. Equally important are social adaptation and prevention of delayed physical development. Children with CHD require personalized nutritional support protocols to compensate for elevated energy expenditure and promote weight gain [60], as well as carefully structured physical rehabilitation programs.

At the macro-organizational level, implementation of such programs is impossible without a transition toward multicenter clinical research. An important breakthrough in this area is the initiative of the Interregional Public Organization of Pediatric Cardiac Surgeons, Society of Congenital Heart Disease Specialists, to establish a National Congenital Heart Disease Registry [61]. The creation of a unified and transparent big-data platform, implementation of universal national standards of care, and development of virtual simulation platforms for regional specialist training will help standardize the highest quality of cardiac surgical care across the country.

Discussion

To objectively assess the scientific potential and strategic trajectory of Russian pediatric cardiac surgery, it is reasonable to compare the Russian research agenda with the priority areas declared by leading international professional societies. Such comparison makes it possible not only to identify points of direct

convergence, where Russian science is aligned with global trends, but also to delineate a distinct agenda shaped by the specific population, organizational, and technological context of the Russian Federation.

Analysis of keynote reports and consensus documents from major international cardiac surgical associations in recent years indicates a global shift in focus from immediate surgical survival toward long-term outcomes and quality of life [3–5]. In this respect, Russian science demonstrates close alignment with global developments [61]. The issue of neurocognitive impairment, actively discussed at major international congresses, is directly and substantially reflected in the research programs of most cardiovascular surgery centers in Russia [29; 30]. As in other countries, Russian investigators have moved from documenting neurologic complications to translational studies of mechanisms of white-matter injury during cardiopulmonary bypass, while developing selective perfusion protocols and implementing early digital monitoring [26–28]. The strategy of early definitive repair of complex defects during the neonatal period, now considered a global standard, is being actively and successfully implemented in Russia as well [61]. Integration of prenatal diagnosis with neonatal surgery and the use of hybrid approaches to stabilize duct-dependent lesions are areas in which Russian surgeons operate within the same clinical and scientific paradigm as leading centers worldwide, achieving outcomes comparable with those reported in major international registries [39; 61].

Management of patients with univentricular hemodynamics remains among the most intensely discussed topics at global surgical forums. The international community is now facing the problem of an aging Fontan population and the increasing burden of Fontan-specific complications, including FALD and protein-losing enteropathy [3]. In response, large multicenter databases are being established worldwide [62]. Russian centers are generating a parallel response by conducting in-depth studies of hemostasis, liver function, and lymphatic system abnormalities in patients with cavopulmonary connections [31; 63; 64]. Russian investigators are likewise moving in parallel with global trends in recognizing the importance of preventing interstage

mortality and optimizing the geometry of extracardiac conduits [36]. A similar pattern is seen in mechanical circulatory support. Whereas international professional communities draw on multinational databases to analyze outcomes of pediatric support systems, Russian centers are addressing the same technological challenge: adaptation of intracorporeal systems for low-body-weight patients [65; 66]. However, because of differences in the availability of pediatric donor organs, Russian research places greater emphasis on mechanical circulatory support not only as a bridge to transplantation but also as a form of prolonged therapy, thereby stimulating the development of unique protocols for the care of critically ill patients [56; 65; 66].

The most striking differences – and the clearest emergence of a distinctive Russian agenda – are observed in the area of biomaterial engineering and the search for ideal prostheses. Practical experience has shown that many historically established autologous tissue valve reconstruction techniques do not provide durable long-term results, eventually leading to neo valve dysfunction and complex reinterventions [49]. Accordingly, Russian research has shifted toward the creation of fundamentally new high-technology devices. Development of a domestic polytetrafluoroethylene transcatheter pulmonary valve represents a unique patented innovation without a direct counterpart in the current mainstream global research pipeline, which remains dominated by conventional biologic prostheses [44]. Within the broader strategy of technological sovereignty, Russian science has also made substantial advances in the development of decellularized conduits adapted to the specific challenges posed by highly reactive neonatal immunity [46]. While many foreign associations remain focused primarily on long-term surveillance of commercially available industry-developed devices, the Russian school has assumed the role of a translational bridge – from fundamental materials science to independent production and clinical implantation of valved conduits [45]. This approach makes Russian cardiac surgical science more autonomous, clinically secure, and technologically flexible.

When compared with the agenda of global professional societies, one area in which Russian

science still needs substantial scaling is work with big data and the creation of comprehensive national registries [39]. Foundational reports at the largest international congresses are now based on analyses of tens of thousands of cases drawn from integrated global databases, allowing development of highly robust predictive models and risk calculators. Historically, the Russian research agenda has been built on deep but often single-center experience from leading institutes. However, the current transformation led by the Interregional Public Organization of Pediatric Cardiac Surgeons, Society of Congenital Heart Disease Specialists, through creation of a unified national registry, indicates that Russian science is moving decisively toward multicenter investigation [9; 61]. This methodological restructuring should, in the near future, make it possible not only to validate unique Russian surgical techniques in large population-based cohorts, but also to present these data globally at the highest level of evidence. Thus, while preserving its distinctive national identity in invention and bioengineering, Russian pediatric cardiac surgery is moving toward full methodological integration with the international scientific community and responding to the most pressing challenges of contemporary global medicine.

Limitations

This study has several limitations. It was conducted as an analytical narrative review and does not claim completeness of a formal systematic literature search or meta-analytic data synthesis. Source selection was thematic and focused on the most significant scientific and practical areas represented in leading Russian centers and the current international literature. As a result, some regional data, local clinical practices, or narrowly specialized publications may not have been represented equally. Nevertheless, this format appears appropriate for the stated objective: to identify the key systemic barriers and strategic development vectors in the field.

Conclusions

The development of pediatric cardiovascular surgery in Russia is determined not only by refinement of surgical techniques, but also by the field's ability

to integrate advances in perinatal medicine, bioengineering, digital technologies, immunology, arrhythmology, rehabilitation, and healthcare organization. Contemporary challenges are primarily related to the growing number of patients with complex anatomy, high comorbidity burden, the need for repeated staged interventions, and the requirement for long-term follow-up after surgery.

The key directions of further progress include the development of predictive diagnostics and referral systems, improvement of organ-protection strategies, creation of domestic bioengineered solutions, implementation of precision digital technologies,

expansion of mechanical circulatory support and transplantation programs, establishment of specialized centers for patients with Fontan circulation and arrhythmologic complications, and construction of a comprehensive system of continuous monitoring and rehabilitation.

The integration of domestic innovation, multicenter collaboration, and national registry data has the potential not only to improve immediate and long-term treatment outcomes, but also to establish a sustainable technological and scientific platform for the future development of pediatric cardiovascular surgery in Russia.

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