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CLINICAL AND NEUROLOGICAL FEATURES OF COMPLICATIONS OF CONGENITAL HEART DEFECTS IN PUBERTY

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Abstract. Most children with congenital heart defects (CHD) now undergo surgical correction or palliation in infancy and survive into adolescence. The neurological consequences of this treatment, however, often become apparent only years later, and puberty is the period when many of them are first recognized. This paper reviews literature published from 2000 to 2025 on the clinical and neurological features of postoperative complications of CHD in adolescents aged 10–19 years. The review shows that these complications fall into three groups. The first group consists of late consequences of perioperative brain injury: deficits in executive function, attention, memory, visuospatial skills and social cognition, attention-deficit/hyperactivity disorder (ADHD) and anxiety, together with structural brain abnormalities on magnetic resonance imaging (MRI), found in 33% of adolescents after the arterial switch operation, 42% after repair of tetralogy of Fallot and 66% after the Fontan procedure. Complications at the first operation, the total number of surgical complications, postoperative seizures and the duration of deep hypothermic circulatory arrest are the main predictors of a poor outcome. The second group consists of delayed postoperative events: ischemic stroke, often clinically silent, thromboembolism in the Fontan circulation, intracranial hemorrhage during anticoagulant therapy, epilepsy, the neurological complications of endocarditis on prosthetic material, and arrhythmic syncope after repair of tetralogy of Fallot. The third group consists of factors specific to puberty: delayed sexual maturation after multiple operations, the start of hormonal contraception, and the transition from pediatric to adult care. Structured neurological follow-up of every adolescent who has undergone heart surgery, a low threshold for neuroimaging, and careful differentiation between arrhythmic syncope and epileptic seizures are the key measures for improving outcomes.

Key words. Congenital heart defects, cardiac surgery, postoperative complications, puberty, adolescence, neurodevelopmental outcome, stroke, epilepsy, Fontan procedure, tetralogy of Fallot, arterial switch operation, thromboembolism.

Introduction. Congenital heart defects are the most common congenital malformations, with a global birth prevalence of about 8 per 1,000 live births [1]. Advances in cardiac surgery, cardiopulmonary bypass and intensive care have changed the prognosis of even the most complex defects, so that most operated children now reach adolescence and adulthood [2, 3]. As a result, the focus of clinical attention has shifted from survival to the long-term consequences of the defect and of its treatment. Neurodevelopmental disorders are now recognized as the most common and most lasting complications in this population [3]. The brain of a child with complex CHD is exposed to several successive insults: abnormal development in utero, hypoxemia before surgery, cardiopulmonary bypass, deep hypothermia or circulatory arrest during the operation, and low cardiac output, seizures

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or stroke in the early postoperative period [2, 3]. After the operation, further risks persist: residual shunts and lesions, thrombosis, the need for anticoagulation, prosthetic material, arrhythmias and repeated interventions [9, 12, 16, 22]. Puberty is a critical period for these patients. Brain maturation continues, academic and social demands rise sharply, and deficits that were mild or undetected in early childhood become clinically apparent [3, 4]. At the same time, adolescents begin to take responsibility for their own treatment, may stop attending follow-up visits and face specific risks such as delayed puberty and the start of hormonal contraception [21, 23, 24]. In pediatric neurological practice, an adolescent who underwent heart surgery in infancy may present with school failure, behavioral change, headache, seizures, syncope or an acute focal deficit, and the link between these symptoms and the earlier operation is often overlooked. The aim of this paper is to review literature published from 2000 to 2025 on the clinical and neurological features of postoperative complications of CHD in puberty, with emphasis on their relation to the type of operation, their differential diagnosis and their prevention.

Literature review. *Late consequences of perioperative brain injury.* The 2012 scientific statement of the American Heart Association (AHA) and the American Academy of Pediatrics defined children who undergo open-heart surgery in infancy as a high-risk group for developmental disorders and recommended routine neurodevelopmental evaluation [2]. The 2024 AHA statement extended this approach across the lifespan and listed surgical and perioperative factors among the main determinants of neurodevelopmental risk, along with genetic, fetal and socioeconomic factors [3]. The most detailed data on adolescent outcomes come from the Boston cohorts. In the Boston Circulatory Arrest Study, infants with transposition of the great arteries were randomly assigned to deep hypothermic circulatory arrest or continuous low-flow cardiopulmonary bypass during the arterial switch operation, and 139 of 159 eligible patients were re-examined at 16 years of age [4]. Among children followed to 8–14 years, impairments were twice as frequent as at 5 years, which shows that deficits become more apparent as academic demands increase [4]. At 16 years, MRI abnormalities were found in 33% of patients compared with 4% of referents [4]. In 91 adolescents aged 13–16 years after repair of tetralogy of Fallot, Bellinger et al. found genetic syndromes in 25% of patients; even patients without a syndrome performed significantly worse than referents in all neuropsychological domains [5]. The strongest predictors of a poor late outcome were a greater number of complications at the first operation, more surgical complications across all operations and the occurrence of postoperative seizures; MRI abnormalities were found in 42% of patients compared with 8% of referents [5]. The most severe changes occur after staged palliation of a single ventricle: among 156 adolescents after the Fontan procedure, any MRI abnormality was found in 66% compared with 6% of referents, and 13% had evidence of stroke, which had not been diagnosed previously in 40% of them [6]. Cassidy et al. showed that executive dysfunction is common in children and adolescents with critical cyanotic CHD [8].

Psychiatric disorders. DeMaso et al. found a lifetime psychiatric diagnosis in 65% of adolescents with single ventricle after the Fontan procedure, compared with 22% of referents, with anxiety disorders and ADHD being the most frequent [7]. Risk factors for anxiety, ADHD and lower psychosocial functioning included a longer duration of deep hypothermic circulatory arrest, lower birth weight, lower intellectual functioning and male sex [7]. These findings link intraoperative factors directly to the mental health of operated patients in adolescence.

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Stroke and thromboembolism. The risk of stroke after cardiac surgery is not limited to the perioperative period. In a community-based case–control study of 2.5 million children younger than 20 years, Fox et al. found that CHD increased the risk of stroke 19-fold and a history of cardiac surgery more than 30-fold; after perioperative strokes were excluded, a history of surgery still increased the risk 13-fold [9]. One patient had a stroke 18 years after the last intervention [9]. In a Swedish national cohort of 25,985 children and young adults with CHD, the risk of ischemic stroke was almost 11 times higher than in controls [10], and in adults with CHD the rate of ischemic stroke before the age of 55 years remained 9 to 12 times higher than in the general population [11]. The Fontan circulation carries a particular risk: slow, non-pulsatile venous flow, prosthetic conduits, atrial arrhythmias and abnormalities of coagulation predispose to thrombosis and to paradoxical embolism through a fenestration or residual shunt [12, 22]. A meta-analysis by Alsaied et al. showed that thromboprophylaxis with aspirin or warfarin significantly lowers the incidence of thromboembolism after the Fontan procedure, with no significant difference between the two drugs [12]. Anticoagulation, in turn, increases the risk of intracranial hemorrhage, especially after head trauma, which is common in active adolescents [19, 22].

Postoperative seizures and epilepsy. Seizures after cardiac surgery in infancy are a marker of brain injury, and in adolescents after repair of tetralogy of Fallot they predicted a worse late neurodevelopmental outcome [5]. Leisner et al. found in a Danish population-based cohort that patients with CHD had a markedly higher risk of epilepsy than controls, and this risk was related to the number of cardiac procedures [13, 14]. A Swedish nationwide study of 71,941 patients with CHD reported a 3.6-fold higher risk of epilepsy and identified stroke as a potentially preventable risk factor [14]. Castillo-Pinto et al. followed 157 children who underwent cardiopulmonary bypass before the age of 2 years: 7.7% had acute postoperative seizures, but only one of them developed epilepsy, and epilepsy developed in 3.2% of the cohort overall [15]. Predictors of epilepsy included a greater number of cardiac operations, the need for extracorporeal membrane oxygenation or a ventricular assist device, and arterial ischemic stroke [15]. Thus, epilepsy in an operated adolescent usually reflects a structural brain injury, most often a stroke, rather than the early postoperative seizures themselves.

Arrhythmias and syncope after repair. Surgical scars, patches and chronic volume or pressure overload create the substrate for arrhythmias. In adults with repaired tetralogy of Fallot, the burden of atrial and ventricular arrhythmias increases with age [16]. Gatzoulis et al. showed that QRS prolongation to 180 ms or more is a predictor of ventricular tachycardia and sudden death late after repair [17]. For the pediatric neurologist this is important because arrhythmic syncope may be accompanied by brief convulsive movements and misdiagnosed as epilepsy. Atrial arrhythmias after Fontan and atrial switch operations are also a source of cardioembolic stroke [16, 22].

Infective endocarditis and brain abscess. Prosthetic valves, conduits, patches and systemic-to-pulmonary shunts placed during surgery increase the risk of infective endocarditis, and the AHA statement notes that the increased survival of operated children and the use of prosthetic materials have changed the epidemiology of endocarditis in childhood [18]. In a multicenter cohort of 1,345 episodes of left-sided endocarditis, neurological complications occurred in 25% of patients; the independent risk factors included large vegetations, Staphylococcus aureus infection, mitral valve involvement and anticoagulant therapy [19]. Patients who have undergone only palliative operations

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and remain cyanotic are also at risk of brain abscess: Atiq et al. found cyanotic CHD in 37% of children with brain abscess, and late diagnosis led to hemiparesis and epilepsy as sequelae [20].

Puberty-specific factors. Menon et al. studied 299 Fontan survivors with a median age of 13.9 years and found that 58% of both boys and girls were delayed by about 1.5 years in at least one Tanner stage parameter; more than two operations before the Fontan procedure was associated with this delay [21]. Estrogen-containing contraceptives increase the risk of thrombosis and should be avoided in girls with a Fontan circulation or residual cyanosis [23]. The AHA recommends a structured program of transition to adult care that begins early in adolescence, because loss to follow-up during this period leads to undetected complications [24].

Research Methodology. This work was designed as a narrative review of the literature on the clinical and neurological features of postoperative complications of CHD in puberty. Sources were searched in the PubMed, Google Scholar and Cochrane Library databases using the key words "congenital heart surgery", "postoperative", "adolescents", "neurodevelopmental outcome", "deep hypothermic circulatory arrest", "arterial switch", "tetralogy of Fallot", "Fontan", "stroke", "thromboembolism", "anticoagulation", "epilepsy", "postoperative seizures", "arrhythmia", "infective endocarditis" and "transition". Original studies, randomized trials with long-term follow-up, population-based cohort and case–control studies, systematic reviews, meta-analyses, scientific statements and clinical guidelines published in English from 2000 to 2025 were included. Puberty was defined as the age range of 10–19 years. Studies of adults were included when they described complications that begin or accumulate in adolescence. Studies limited to the immediate perioperative outcome without long-term follow-up were excluded. The selected sources were analyzed by the following criteria: type of operation, mechanism of the complication, neurological and other clinical signs in adolescents, predictors, differential diagnosis, outcome and prevention. The data were summarized descriptively and presented in tabular form.

Results and discussion. Analysis of the literature shows that the neurological picture in operated adolescents is shaped by three factors: brain injury sustained before, during and soon after the operation; delayed complications of the repaired or palliated circulation; and the age-specific changes of puberty. The late neurological outcome differs markedly by type of operation (Table 1).

Table 1. Late neurological outcome in adolescents by type of cardiac operation [4–7, 12, 16, 17, 19, 20, 22].

Operation	Main neurological findings in adolescence	MRI findings	Predictors and specific risks
Arterial switch operation for transposition of the great arteries	Deficits in academic achievement, memory, executive function, visuospatial skills, attention and social cognition; deficits become more apparent with age	Abnormalities in 33% versus 4% of referents [4]	Method of vital organ support (circulatory arrest or low-flow bypass), postoperative seizures [4]
Repair of tetralogy of Fallot	Lower scores than referents in all neuropsychological domains, worse in genetic syndromes (25%)	Abnormalities in 42% versus 8% of referents [5]	Complications at the first operation, total surgical complications, postoperative seizures [5]; late ventricular

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Operation	Main neurological findings in adolescence	MRI findings	Predictors and specific risks
			arrhythmias and syncope, risk rises with QRS ≥180 ms [16, 17]
Staged palliation ending in the Fontan procedure	Most severe cognitive deficits; psychiatric diagnosis in 65%, mainly anxiety and ADHD [7]	Abnormalities in 66% versus 6%; evidence of stroke in 13%, undiagnosed in 40% of them [6]	Duration of deep hypothermic circulatory arrest [7]; thromboembolism, atrial arrhythmias, anticoagulation [12, 22]
Palliative systemic-to-pulmonary shunt with residual cyanosis	Risk of brain abscess, hyperviscosity symptoms, paradoxical embolism	Abscess or infarcts on neuroimaging	Late diagnosis of abscess leads to hemiparesis and epilepsy [20]
Implantation of prosthetic valves and conduits	Neurological complications of endocarditis; hemorrhage during anticoagulation	Embolic infarcts, hemorrhage	Large vegetations, Staphylococcus aureus, anticoagulant therapy [19]

As Table 1 shows, the frequency of structural brain abnormalities in adolescence increases with the complexity of the operation, from one-third of patients after the arterial switch operation to two-thirds after the Fontan procedure [4–6]. A considerable share of brain injury remains clinically silent: 40% of strokes in Fontan adolescents had not been diagnosed before research MRI [6]. For this reason, declining school performance or a new behavioral change in an operated adolescent should be regarded as a possible sign of brain injury. The main postoperative neurological complications that may develop or first present in puberty are summarized in Table 2.

Table 2. Postoperative neurological complications in adolescents with congenital heart defects [3, 5–7, 9–19, 21–24].

Complication	Main mechanism	Neurological signs in adolescents	Key data	Prevention
Neurocognitive and executive dysfunction	Cumulative perioperative brain injury, genetic factors	Poor attention, planning and memory, declining school performance	Deficits even in patients without a syndrome [5]	Repeated neuropsychological assessment, educational support [3]
Psychiatric disorders	Brain injury, chronic illness, psychosocial stress	ADHD, anxiety, depression	Psychiatric diagnosis in 65% versus 22% after Fontan [7]	Screening and early referral [3, 7]

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Complication	Main mechanism	Neurological signs in adolescents	Key data	Prevention
Ischemic stroke, including silent infarcts	Thrombosis, paradoxical embolism, atrial arrhythmias	Hemiparesis, aphasia, visual field loss, focal seizures, cognitive decline	Surgery increases stroke risk more than 30-fold; risk persists for years [9]	Thromboprophylaxis after Fontan [12], rhythm control, avoidance of estrogen [23]
Intracranial hemorrhage	Anticoagulant therapy, head trauma, septic aneurysm	Sudden headache, vomiting, depressed consciousness, focal signs	Anticoagulation is a risk factor for hemorrhage in endocarditis [19]	Control of anticoagulation, education about trauma [22]
Epilepsy	Structural brain injury, most often stroke	Focal and generalized seizures	Risk related to the number of procedures [13]; predictors include repeated surgery, ECMO and stroke [15]	Prevention of stroke [14]
Arrhythmic syncope	Scars, patches, ventricular overload	Sudden loss of consciousness, sometimes with brief jerks	QRS ≥180 ms predicts ventricular tachycardia and sudden death after tetralogy repair [17]	ECG and Holter monitoring, electrophysiological assessment [16]
Neurological complications of endocarditis	Septic embolism from prosthetic material	Stroke, encephalopathy, meningitis, hemorrhage	Neurological complications in 25% of episodes [19]	Oral hygiene, education about endocarditis [18]
Delayed puberty	More than two operations before Fontan	Lower self-esteem, emotional problems	Delay of about 1.5 years in 58% [21]	Monitoring of growth and Tanner stage, endocrine referral [21]

The most common diagnostic problem in neurological practice is an acute neurological event in an adolescent who has undergone heart surgery. Transient loss of consciousness with convulsive movements may be an epileptic seizure caused by an old infarct or an arrhythmic syncope, and an acute focal deficit may be due to embolic stroke, hemorrhage during anticoagulation, endocarditis or brain abscess. The key differential features are summarized in Table 3.

Table 3. Differential diagnosis of acute neurological events in an adolescent after surgery for congenital heart disease (compiled by the authors on the basis of [9, 12, 15–20, 22, 25]).

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Condition	Key history	Clinical features	Investigations	Urgent action
Arrhythmic syncope	Repair of tetralogy of Fallot, Fontan or atrial switch; palpitations; syncope during exercise	Sudden loss of consciousness, pallor, brief jerks, rapid recovery without postictal confusion	Wide QRS, arrhythmia on ECG or Holter monitoring; normal EEG	Cardiological assessment; antiepileptic drugs are not indicated
Epileptic seizure	Previous stroke, postoperative seizures, multiple operations	Aura, tonic–clonic seizure, tongue biting, postictal confusion	Epileptiform activity on EEG; old infarct or gliosis on MRI	Antiepileptic therapy; search for a new cerebrovascular event
Embolic ischemic stroke	Fontan, fenestration or residual shunt, atrial arrhythmia, interruption of thromboprophylaxis, estrogen-containing contraceptives	Sudden hemiparesis, aphasia, visual field loss	Infarct on diffusion-weighted MRI; thrombus or shunt on echocardiography	Stroke protocol; assessment of the embolic source
Intracranial hemorrhage	Anticoagulant therapy, head trauma, endocarditis	Sudden severe headache, vomiting, depressed consciousness, focal signs	Hemorrhage on CT; prolonged INR	Reversal of anticoagulation; neurosurgical consultation
Endocarditis-related stroke or meningitis	Prosthetic valve or conduit, prolonged fever, dental infection	Fever, focal deficit, meningeal signs, new heart murmur	Positive blood cultures, vegetations on echocardiography	Antibiotics; assessment for cardiac surgery
Brain abscess	Palliated cyanotic defect with right-to-left shunt	Progressive headache, fever (may be absent), vomiting, seizures, focal signs	Ring-enhancing lesion on CT or MRI	Antibiotics and neurosurgical drainage
Migraine with aura	Recurrent episodes, family history, residual right-to-left shunt	Visual or sensory aura followed by headache, full recovery	Normal neuroimaging	Diagnosis of exclusion at the first episode

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As Table 3 shows, a detailed history of the operation and of current treatment is the key to diagnosis. Every operated adolescent with a first episode of loss of consciousness should have an electrocardiogram before antiepileptic treatment is started, because arrhythmic syncope after repair of tetralogy of Fallot carries a risk of sudden death [16, 17]. An acute focal deficit requires urgent neuroimaging and echocardiography, and in a patient on anticoagulants, computed tomography to exclude hemorrhage [19, 22]. Prevention is based on current recommendations: routine neurodevelopmental and psychiatric screening of all patients who have undergone open-heart surgery in infancy [2, 3, 7], thromboprophylaxis after the Fontan procedure [12], rhythm monitoring after repair [16, 17], oral hygiene and education about endocarditis [18], avoidance of estrogen-containing contraception in high-risk patients [23], and a structured transition to adult care [24]. In our view, further research is needed on the frequency and spectrum of postoperative neurological complications in adolescents operated for CHD in Uzbekistan, on the role of screening MRI in detecting silent infarcts, and on the relation between the type and number of operations and the neurological outcome in adolescence.

Conclusion. The neurological consequences of surgery for congenital heart defects often become apparent only in puberty, when brain maturation continues and academic and social demands increase. Late consequences of perioperative brain injury include deficits in executive function, attention, memory and social cognition, ADHD and anxiety. Structural brain abnormalities are found in one-third of adolescents after the arterial switch operation, in 42% after repair of tetralogy of Fallot and in two-thirds after the Fontan procedure, and a considerable share of strokes remain clinically silent. Complications at the first operation, the total number of surgical complications, postoperative seizures and the duration of deep hypothermic circulatory arrest are the main predictors of a poor outcome. Delayed postoperative complications include ischemic stroke, whose risk remains elevated for many years after surgery, thromboembolism in the Fontan circulation, intracranial hemorrhage during anticoagulation, epilepsy related to structural brain injury, neurological complications of endocarditis on prosthetic material and arrhythmic syncope after repair of tetralogy of Fallot. Puberty adds delayed sexual maturation after multiple operations, the risks of hormonal contraception and loss to follow-up during the transition to adult care. Every adolescent who has undergone heart surgery should therefore receive structured neurological and neuropsychological follow-up; declining school performance should be regarded as a possible sign of brain injury; an electrocardiogram should be recorded in every operated adolescent with a first episode of loss of consciousness; and an acute focal deficit requires urgent neuroimaging. Close cooperation between the pediatric neurologist, the cardiologist and the cardiac surgeon is the key to improving the neurological outcome of these patients.

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