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Review

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Anesthetic management in pediatric cardiac surgery

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ABSTRACT

Pediatric cardiac anesthesia poses significant challenges due to the complexity of congenital heart diseases (CHDs) and the distinct physiological considerations in children. Despite advancements in surgical and anesthetic techniques, many regions still struggle to provide adequate cardiac care, while some areas perform a high volume of pediatric cardiac surgeries annually. This review explores the development and physiology of the cardiovascular system, focusing on congenital heart defects and their impact on anesthesia management. It discusses the roles of cardiopulmonary bypass (CPB) and cardiac catheterization in diagnosis and treatment, as well as essential aspects of preoperative, intraoperative, and postoperative care. Emphasis is placed on effective anesthesia strategies, early extubation, and optimal recovery practices. Ongoing advancements in technology and clinical practice are vital for enhancing safety and outcomes in pediatric cardiac anesthesia.

Keywords: Anesthesia, cardiac, pediatric, congenital heart disease, cardiopulmonary bypass

INTRODUCTION

Pediatric cardiac surgeries pose significant challenges for anesthesiologists due to the complexity of congenital heart diseases (CHDs) and the unique physiological considerations in children. Because of the improvements in surgical techniques, diagnosis, perfusion, and anesthesia; anesthesiologists encounter patients with cardiac diseases more. These patients can have both cardiac and non-cardiac procedures. But still, almost 90% of a million children worldwide can't have adequate medical care.[1] The World Health Organization (WHO) recommends that 300-500 pediatric cardiac surgeries be performed annually per 2 million population.[2] In our country, over 4.000 pediatric congenital heart surgeries are conducted annually.[3]

Congenital heart disease, present at birth, includes functional, structural, or positional heart defects. Severe forms can be 12 times more fatal during infancy and occur in 5-14 per 1.000 live births.[4] Untreated, these defects can lead to serious complications such as infective endocarditis, multi-organ dysfunction, and pulmonary hypertension.[2] Cardiac anomalies may be genetic, non-genetic, or multifactorial, while acquired cardiac diseases often result from conditions like endomyocardial fibrosis, rheumatic heart disease, Chagas disease, and Kawasaki disease. Without proper medical treatment, these will be fatal, too.[5]

Common congenital heart conditions include hypoplastic left-heart syndrome, tetralogy of Fallot, ventricular septal defect, atrioventricular septal defects, and cardiomyopathy. Patients with these conditions often require both cardiac and non-cardiac procedures.[6] When administering anesthesia to pediatric patients with CHDs, it is crucial to understand the underlying pathology, the specific procedure, and the effects of anesthetics on the cardiovascular system.

CARDIOVASCULAR DEVELOPMENT

The human embryo relies on uteroplacental diffusion in the first two weeks. After that, the embryo becomes a bilaminar disk that formed from the epiblast and hypoblast. The cardiovascular system is the first to develop, starting in the third week. The embryo transforms into a trilaminar disc through gastrulation, forming all three germ layers; ectoderm, mesoderm, and endoderm. In the epiblast, cardiac progenitor cells migrate to the lateral plate mesoderm cranially and laterally after gastrulation. This is divided into somatic (dorsal) and splanchnic (ventral) layers. The somatic layer generates the pericardium, while the splanchnic layer generates the myocardium, dependent on signals from the endoderm. These embryonic cells are generated not only from the heart mesoderm but also from the cardiac neural crest and proepicardium.[7]

FETAL CIRCULATION

Fetal circulation is significantly different from that of adults. This system helps the fetus obtain oxygenated blood and nutrients from the placenta via two umbilical arteries and one umbilical vein. The lungs are bypassed via the ductus arteriosus, and the liver via the ductus venosus. Blood passes from the right atrium to the left atrium via the foramen ovale. Normal fetal heart rate is 100-160 beats per minute. Fetuses have decreased ventricular filling and reduced contractility compared to adults. After birth, this circulation goes under a rapid change. First, it changes the shunt's way in ductus arteriosus to the left to right and then closes both the shunt and the foramen ovale. If these changes do not occur properly, defects arise.[8]

Congenital heart diseases often result from these shunts not closing properly after birth. These abnormalities can alter blood circulation, leading to cyanotic or acyanotic defects. Cyanotic heart defects arise from right-to-left shunts, where deoxygenated blood bypasses the lungs and enters systemic circulation. Acyanotic heart diseases result from left to right shunts, which occur after birth. If not properly corrected, these shunts can reverse over time, leading to Eisenmenger syndrome (**Table 1**).[8]

Table 1. Cyanotic and acyanotic heart diseases

Cyanotic heart diseases	Acyanotic heart diseases
Tetralogy of fallot (TOF)	Ventricular septal defect (VSD)
Transposition of the great arteries (TGA)	Atrial septal defect (ASD)
Tricuspid atresia	Patent ductus arteriosus (PDA)
Total anomalous pulmonary venous connection (TAPVC)	Atrioventricular septal defect (AVSD)
Pulmonary atresia	Coarctation of the aorta
Hypoplastic left heart syndrome	Pulmonary stenosis
Ebstein's anomaly	Aortic stenosis
	Mitral valve prolapse

Cardiopulmonary bypass (CPB) is used in major heart or vessel surgeries to isolate the cardiopulmonary system, creating an ideal surgical field. The bypass must fulfill the functions of the heart and lungs, providing oxygen to the blood, removing carbon dioxide, ensuring adequate perfusion to all organs, and minimizing harm.[9]

Some selected cases can be done off pump without the requirement of a CPB as known as beating heart surgery. Although there are more studies on adults, it can be applicable in pediatrics, too (**Table 2**).[10]

Table 2. On-pump and off-pump pediatric cardiac procedures

On-pump cardiac surgeries	Off-pump cardiac surgeries
TOF	PDA
VSD	Coarctation of the aorta
ASD	Blalock-taussing shunt
AVSD	Pulmonary artery banding
TGA	Closed mitral commissurotomy

TOF: Tetralogy of fallot, VSD: Ventricular septal defect, ASD: Atrial septal defect, AVSD: Atrioventricular septal defect, TGA: Transposition of the great arteries, PDA: Patent ductus arteriosus

Cardiac catheterization is used both for diagnostics and treatments, such as repairing atrial or ventricular septal defects, coil embolization of systemic collaterals, addressing coarctation of the aorta, placing stents in stenotic pulmonary vessels, performing balloon valvuloplasty, and conducting radiofrequency ablation. However, less invasive diagnostic methods like echocardiography or magnetic resonance imaging are increasingly preferred. Anesthetists should review these reports to manage patient care effectively.[11]

PREOPERATIVE CARE

In preoperative care selecting appropriate patients for the team and facility conditions is crucial. The success of perioperative processes depends on this period to foresee potential risks and prepare accordingly. Evaluating the patient's medical history, comorbidities, physical examination, specifics of the cardiac defect, previous surgeries or interventions, and diagnostic tests is essential. Preparation for intra- and postoperative requirements must begin early. It should be remembered that all these processes are multidisciplinary. Routine care such as dental care, immunizations, and medication management should be addressed.[5]

Patients with restricted cardiac reserve may exhibit symptoms like tachypnea, dyspnea, frequent lung infections, feeding difficulties, and sweating, older children may show difficulty in activities with peers, exercise intolerance, tiredness, orthopnea, chest pain, palpitation, or syncope **Figure 1**.[12] In heart failure, symptoms can include tachypnea, chest retraction, nasal flaring, accessory muscle breathing, pedal edema, jugular vein distention, hepatomegaly, and rales. Peripheral pulses and blood pressure should be checked in all extremities, along with pulse oxygen saturation. Recent upper or lower respiratory infections can cause airway reactivity for 2-8 weeks.[13]

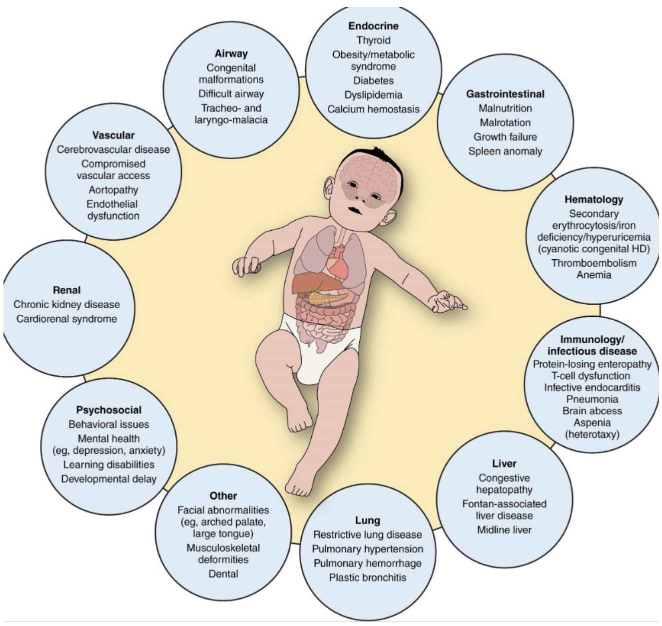

Figure 1. Noncardiac conditions in patients with congenital heart disease
HD: Heart disease

Premedication is important in children to reduce anxiety and ease separation from their parents. But deep sedation should be avoided because it may lead to hypoventilation-related hypercarbia which can result in pulmonary hypertension.

Oxygen saturation should be tracked monitored throughout. Midazolam can be administered at 0.5 mg/kg (max 20 mg) orally or 0.05-0.2 mg/kg intravenously. Alternatives include 50-75 mg/kg pedikloril, ketamine (1-2 mg/kg intravenous, 5 mg/kg oral, 2-5mg/kg intramuscular).[13] Additionally, dexmedetomidine can be considered. For transnasal administration, the dosage ranges between 0.2 and 4.0 µg/kg. However, a dose of 0.5 µg/kg is typically used in children under 6 months, while 1.0 µg/kg is applicable in older children. For oral administration, a dose of 2 µg/kg is recommended.[14,15]

INTRAOPERATIVE CARE

To avoid hypothermia, the operating room temperature, heated surgical table pads, and blankets should be prepared before surgery. Catheters, cannulas, perfusion pumps, and appropriate infusion lines should be ready, ensuring air bubbles are removed. Blood products should be prepared in anticipation of potential bleeding.[3]

In addition to standard ASA monitors (ECG, noninvasive blood pressure, heart rate, peripheric arterial saturation) invasive blood pressure, capnography, central venous pressure catheter, pulmonary artery pressure, and body temperature monitors may be required. Also, cerebral oxygenation (NIRS), bispectral index (BIS), and advanced hemodynamic monitors should be used. In these patients, wide intravenous access is often needed. Ultrasound guidance is mandatory for these procedures. Transesophageal echocardiography is also utilized.

The induction method depends on the child's age: inhalation induction is useful for younger children, while intravenous induction is preferred for older ones. Sevoflurane is the first choice for inhalation induction and maintenance. For IV induction, propofol or ketamine can be used. It should be kept in mind that the altered systemic and pulmonary vascular resistance can affect shunts and cardiac output during this process. Neuromuscular blockers are needed for tracheal intubation, and fentanyl (1-2 µg/kg) can suppress hemodynamic responses.[13]

Remifentanil can be used for both induction (1.5 µg/kg) and maintenance (0.2–0.5 µg/kg/min, continuously injected by infusion pump), which also allows for fast-track anesthesia. Opioid usage in cardiac anesthesia is preferred for their analgesic effects and minimal impact on hemodynamics.[16]

Transesophageal echocardiography is one of the most important cardiovascular imaging methods. Since the esophagus is close to the heart and major vessels, it is a perfect ultrasonic window. It provides more accurate information in many specific diagnostic and catheterization procedures than transthoracic echocardiography (TTE). Results are examined after anesthesia induction, before entering CPB, during surgery, and after coming off CPB. In this way, the need for reoperation is reduced.[3]

High inspiratory oxygen concentrations can decrease pulmonary vascular resistance and cause an increase in the left to right shunts. It is convenient to use a mixture of oxygen and air.[13]

For arterial cannulation, using 24-gauge catheters for patients under two years, and 22-gauge for those over two years would be appropriate. Central venous catheters typically vary according to weight: a 4 French (4F) double lumen for patients under 5 kg, a 5 French (5F) triple lumen for 5-20 kg, and a 7 French (7F) triple lumen for over 20 kg. Ultrasound guidance would be beneficial for these procedures. Finally, for temperature tracking, a nasopharyngeal probe can be chosen.[3]

During surgeries involving a CPB machine, it is crucial to maintain an activated clotting time (ACT) of over 480 seconds. Heparin sodium, administered at a dose of 3-4 mg/kg, ensures this. Cardioplegia is administered to arrest the heart, a process that should be repeated systematically over time. Regular monitoring of arterial blood gas analyses, electrolytes, and hemoglobin levels is essential. Hypothermia, cardioplegia, and hemodilution techniques are employed in open-heart surgeries to preserve myocardial viability and facilitate its return to normal function following the removal of the cross-clamp. Research indicates that cooling the myocardium to temperatures between 28-32°C does not disrupt myocardial metabolism and maintains optimal function compared to normothermic conditions (37°C). Cardioplegia not only arrests the heart but also provides essential nutrients that meet the myocardium's energy demands. This approach reduces anaerobic metabolism and protects the heart during ischemic periods. While there is no universal consensus in the literature regarding the best cardioplegia solution, various formulations are used in clinical practice.[3]

Hypotermia is when body core temperature is below 35°C. In cardiac surgery there are four stages of hypotermia as mild (32°C–35°C), moderate (31–26°C, deep (25–20°C), and profound (<20°C). There are some new approaches where cpb done under normothermia (35°C up to 37°C). In a study on av defects normothermic patients showed lower lactic asidosis, better coagulation results, less inotrop usage, and better postoperative period.[17]

In a metaanalysis, there is reduced serum lactate, creatine levels and cpb duration time in normothermic group. However it suggests no strong evidence about adverse events and mortality.[18]

It is evident that there is no single approach in medicine. Therefore the temperature management should be done according to selected surgery and patient.

Inotropic agents like epinephrine, milrinone, dobutamine, and dopamine, and vasopressors like norepinephrine, may be needed.[19]

To prevent nausea and vomiting, intravenous antiemetics such as dexamethasone (0.2-0.5 mg/kg) or ondansetron (0.1 mg/kg, max 4 mg) can be administered.

Preemptive nerve blocks are used for postoperative analgesia. They additionally reduce intraoperative opioid consumption and enhance hemodynamic stability.[20] These blocks also attenuate proinflammatory cytokine release during surgery.[21] Intercostal nerve blocks are used for this purpose. Various approaches such as pectointercostal fascial block (PIFB) and transversus thoracic plane block (TTPB) have been developed to optimize outcomes. These blocks, administered with ultrasound guidance, target anterior chest wall pain by depositing anesthetic (typically ropivacaine, bupivacaine, or lidocaine) between specific muscle layers—either between the pectoralis major and intercostal muscles (PIFB) or between the internal intercostal and transversus thoracis muscles (TTPB).[22] The other blocks that can be beneficial are pectoral nerve (PECS) blocks, erector spinae plane block (ESPB), retrolaminar block (RLB), and paravertebral block (PVB). The PECS block (I and II) targets the pectoral and serratus planes, utilizing agents like ropivacaine or bupivacaine to alleviate pain in the breast and upper chest. The ESPB injects anesthetic (e.g., ropivacaine or bupivacaine) between the erector spinae muscle and transverse processes, offering extensive thoracic analgesia suitable for both acute and chronic pain management. The RLB uses bupivacaine along the vertebral lamina for effective thoracic pain relief, particularly in traumatic cases. Lastly, the PVB administers anesthetic, such as ropivacaine or levobupivacaine, near the vertebrae for unilateral chest and abdominal wall analgesia, making it ideal for various surgical procedures in pediatric cardiac care.[23]

Tracking blood glucose is crucial, especially in infants. It is essential to carefully control fluid infusion rates, which aids in calculating blood loss and managing fluids. Renal failure is a significant concern during these processes, particularly due to the nephrotoxic effects of contrast agents used in catheterization. Risk factors include pre-existing renal disease, diabetes mellitus, heart failure, and concurrent use of other nephrotoxic agents. Despite precautions, renal failure remains a potential complication. To mitigate risks, it is important to avoid dehydration and exercise caution with contrast agents.[13] However, excessive fluid administration can worsen cardiac function, highlighting the necessity of maintaining a delicate balance.

The choice of fluids is also important **Figure 2**.[13] Mostly preferred ones in clinical use are crystalloids, balanced crystalloids, and human albumin **Figure 3**.[13] The administration of HES during surgery is not recommended because it increases the risk of mortality, renal dysfunction, and postoperative bleeding.[24]

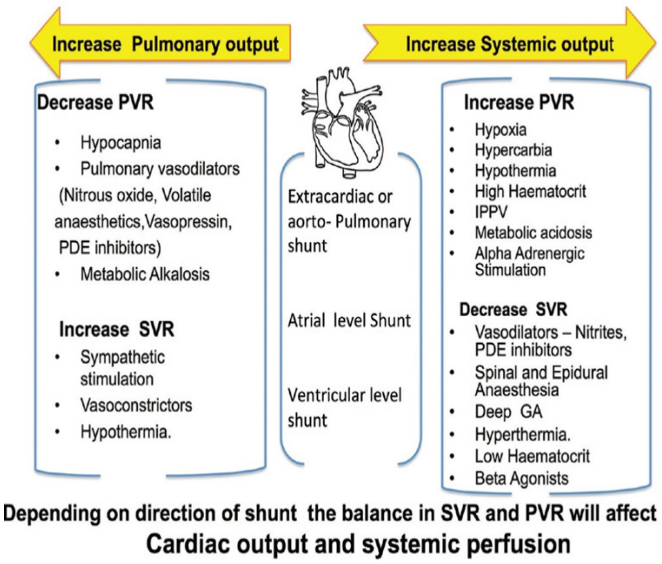

Figure 2. Flow distribution dynamics
PVR: Pulmonary vascular resistance, SVR: Systemic vascular resistance

Anaesthetic drug	SVR	PVR	Dose
Potent volatile agents	↓	↓	0.5-1 MAC
Nitrous oxide	-	↑	
Opioids			
Fentanyl	↓		1-2 μg/kg 0.5-2 μg/kg/h
Morphine	↓		0.05-0.2 mg/kg 0.02-0.2 mg/kg/h
Midazolam	-	-	0.5 mg/kg PO 0.1 mg/kg IV 0.02-0.3 mg/kg/h
Ketamine (with glycopyrrolate)	↑	No effect (if CO_2 normal)	3-4 mg/kg PO 1-2 mg/kg IV 5-20 μg/kg/min
Propofol	↓	-	2-3 mg/kg 100-300 μg/kg/min
Dexmedetomidine	↑-↓	↓	1 μg/kg (over 10 min) 0.2-1 μg/kg/h

IV – Intravenous; SVR – Systemic vascular resistance; PVR – Pulmonary vascular resistance; MAC – Minimum Alveolar Concentration ; ↓ – lowers; ↑ – increases

Figure 3. Anesthetic drug effects and doses

POSTOPERATIVE CARE

After surgery, most patients are transferred to the intensive care unit (ICU) while still intubated, monitored, and receiving continued perfusions. The goals of postoperative care include planning for early extubation, mobilization, and recovery, with a focus on minimizing ICU and hospital stays to reduce morbidity and mortality. Dedicated critical care is crucial at this stage. The impact of postoperative pain cannot be ignored. We know that we deal with opioid-related side effects in some patients. Efficient pain management is essential for enhanced recovery strategies which can improve the outcomes. Intravenous opioid administration is still the main treatment in many practices due to the risk of epidural hematoma or bleeding. Utilizing peripheral nerve blocks can be beneficial in reducing opioid use. Multimodal approaches will help to reduce our concerns. It will also help with intraoperative reduced opioid usage, early extubation, etc. In pediatric cardiac surgery, there is ongoing debate on strategies for enhanced recovery after surgery. The American Association for Thoracic Surgery suggests considering regional anesthesia techniques for optimal outcomes.[5,25]

It's crucial to recognize that spending extended periods in such environments is particularly challenging for pediatric patients. Therefore, optimizing conditions and minimizing this time are paramount. Early extubation plays a pivotal role in achieving these goals.

Early extubation is associated with improved left heart function post-CPB, as mechanical ventilation can decrease preload during inspiration, increasing intrathoracic pressure.[26] Therefore with early extubation, improvement in the blood circulation is a significant outcome after cardiac surgery.[27] Fast-track anesthesia facilitates in-room extubation for suitable patients, potentially improving postoperative outcomes. Pulmonary hypertension remains a significant risk factor for postoperative mortality, exacerbated by surgery and anesthesia-induced factors.[28] Managing hypoxia, hypercarbia, and acidosis to prevent pulmonary vasoconstriction is crucial. Techniques like applying PEEP (approximately 6 cm H_2O) and alveolar recruitment maneuvers aim to mitigate atelectasis during the perioperative period.[22]

Prior to surgery, cardiac catheterization plays a crucial role in diagnosis and disease management. While advancements in techniques and equipment have improved outcomes, understanding and managing relative risks remain essential. Children may require ICU care before or after catheterization, with common adverse effects including the need for mechanical ventilation and hypotension necessitating vasoactive medications.[29]

In cardiac surgery, antifibrinolytics like tranexamic acid (TXA), ε-aminocaproic acid (EACA), and aprotinin have demonstrated significant benefits. These medications primarily reduce postoperative bleeding and diminish the requirement for blood product transfusions.[30] However, there remains a notable gap in large-scale randomized controlled trials investigating the effects and potential side effects of these drugs specifically in pediatric patients.

It should be kept in mind that there can be some complications during these procedures (**Table 3**).[31]

Table 3. Cardiac procedure complications

Arrhythmias	• Sepsis
Low cardiac output syndrome	• Coagulopathy
Heart failure	• Anemia
Pericardial effusion or tamponade	• Thrombosis
• Pulmonary hypertension	• Acute kidney injury (AKI)
• Atelectasis	• Electrolyte imbalances
• Respiratory failure	• Necrotizing enterocolitis (NEC)
• Stroke	• Feeding intolerance
• Seizures	• Delayed awakening
• Neurodevelopmental delays	• Airway complications
• Wound infection	• Post-traumatic stress disorder (PTSD)
• Endocarditis	• Developmental delays

CONCLUSION

In pediatric cardiac surgery, the anesthesiologist plays a pivotal role in ensuring optimal outcomes for patients undergoing complex procedures. This specialty faces significant challenges due to the potential for mortality and morbidity in this vulnerable population. A comprehensive understanding of the unique physiological challenges—such as altered hemodynamics, respiratory mechanics, and complications arising from congenital heart defects—is essential. A qualified multidisciplinary team, involving surgeons, cardiologists, and anesthesiologists, is paramount for effectively managing these cases and tailoring the anesthetic plan to each patient's specific needs.

Recommended medications for anesthesia induction and maintenance include agents like propofol, sevoflurane, and fentanyl, each selected for their safety profiles and pharmacokinetic properties in children. Adjuvant medications, such as dexmedetomidine, can enhance sedation and analgesia while reducing opioid requirements, improving patient comfort during and after surgery. Careful selection of neuromuscular blockers is also critical, particularly in patients with pre-existing neuromuscular compromise, to prevent residual paralysis postoperatively.

Effective hemodynamic monitoring during surgery is crucial, as congenital heart defect patients present unique challenges that can impact cardiac output and systemic perfusion. The use of invasive monitoring techniques, such as arterial lines and central venous catheters, allows for accurate assessment and timely intervention when necessary. Anesthesiologists must remain vigilant in recognizing and managing intraoperative complications, including arrhythmias, hypotension, or changes in oxygenation.

Advances in antenatal diagnosis have enabled earlier identification and intervention for these patients, underscoring the importance of comprehensive care and early intervention. The focus must remain on employing the best anesthetic techniques to ensure patient safety and optimal surgical outcomes. Fast-tracking surgery through early extubation and enhancing perioperative pain management with regional blocks are critical strategies for improving recovery and minimizing postoperative discomfort.

In conclusion, the anesthesiologist's involvement in pediatric cardiac surgery extends beyond the operating room to include postoperative care, pain management, and sedation strategies. Continuous evaluation of current literature is essential for staying informed about emerging evidence regarding anesthetic techniques, drug efficacy, and patient safety protocols. By integrating the latest findings with clinical practice, anesthesiologists can enhance the quality of care delivered to this vulnerable patient population, ultimately improving surgical outcomes and long-term prognoses.

ETHICAL DECLARATIONS

Referee Evaluation Process

Externally peer-reviewed.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

All of the authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version.

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