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Research article

# Efficiency of an algorithm for the prevention of sternal infection after cardiac surgery in children under 1 year of age: A single-center retrospective study

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A R T I C L E I N F O

*Keywords:*
Sternal infection
Wound infection in pediatric
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Complication in pediatric cardiac surgery
Sternal instability
Mediastinitis

A B S T R A C T

*Background:* Sternal infection is one of the most challenging complications to manage after heart surgery. The aim of our study is to evaluate the effectiveness of a developed algorithm for preventing sternal infection in pediatric patients after surgery for congenital heart disease (CHD).
*Methods:* We conducted a single-center study examining the treatment of 478 children with CHD. Patients were divided into 2 groups, taking into account the application of a developed management algorithm. A multivariate logistic regression analysis was used to identify the factors influencing the development of sternal infection following heart surgery using median sternotomy.
*Results:* A developed algorithm was applied in 308 children. In total, there were 16 cases of sternal infection (3.34 %) across both groups. Deep wound infection developed in 6 patients (1.26 %). Sternal infection developed in 2 children (0.65 %) in the first group (in which the algorithm was applied) and 14 children (8.2 %) in the second group. Deep sternal infection developed in 1 patient in the first group (0.33 %) and in 5 patients in the second group (2.94 %). As a result, perioperative risk factors as postoperative resternotomy (OR 23.315; $p < 0.001$), delayed sternal closure (OR 9.087; $p = 0.003$), development of acute renal failure (OR 5.322; $p = 0.018$) were associated with increased risk of infection and application of the developed algorithm resulted in a significant reduction in risk (OR 0.032; $p < 0.001$).
*Conclusion:* The suggested method for the prevention of sternal infection has significantly reduced the incidence of sternal infection after cardiac surgery in children less than 1 year of age. In patients with moderate to high risk for surgical site infection, surgeons can enhance wound healing and prevent wound infections with simple, inexpensive, and readily available tools and techniques. Surgical aspects, topical use of antibiotics, prevention of peripheral vasoconstriction, maintenance of normal oxygen delivery rates, and an individual approach to intensive care are essential.

## 1. Introduction

Sternal infection is one of the most formidable and challenging complications to manage after heart surgery involving median sternotomy. It has a significant impact on patient outcomes. The incidence of this complication in children after cardiac surgery ranges

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from 1.5 to 34 % [1–5]. The treatment of such complications is often associated with a high level of mortality, a significant increase in the duration and cost of hospital stay [6,7]. One effective method of treatment is vacuum therapy for infected wounds [1,8–10], especially if muscle flap repair of a wound defect is required. High early mortality rates are noted if sternal wound infection occurs. For instance, in children under one month old, mortality ranges from 31 to 46 % [4,11]. In addition, it should be taken into account that plastic surgery of chest defects using various muscle flaps is a highly traumatic, crippling method and it is often accompanied by a risk of severe secondary complications. Among the latter are persistent infection (mediastinitis, abscess), flap necrosis, impaired respiratory mechanics, shoulder and upper limb function, as well as hernia formation at the site of the sternal defect and the donor zone [11–14].

The authors of most studies on the management of sternal infection in children believe that prevention of this complication is the most desirable approach [3,11,15,16]. An important component of preventing the development of sternal infection is the assessment of all risk factors [17,18]. There are few recommendations on measures to prevent sternal wound infection in children after cardiac surgery, so one has either to refer to recommendations for adults or to develop methods for its prevention [3,11,19–21]. However, the risk factors in pediatric cardiac surgery are different, and therefore methods to prevent the development of wound infection are partially applicable. It is advisable to divide the risk factors for the development of complications in accordance with the stages of patients' treatment: preoperative, intraoperative, postoperative. The main risk factors for the pediatric category according to various studies [2–5,7,8,15,22–27] are.

- preoperative: age under 1 year old, cyanotic CHD, a genetic syndrome, hospitalization exceeding 48 h before surgery and high risk according to the ASA scale (American Society of Anesthesiologists' Patient Assessment Scale).
- intraoperative: delayed wound closure, intraoperative hypothermia, circulatory arrest, duration of surgery, aortic cross-clamping and cardiopulmonary bypass (CPB), asymmetric sternotomy, excessive electrocoagulation, use of wax to stop bleeding from the sternum, use of foreign materials in the wound, inadequate wound drainage.
- postoperative: extracorporeal membrane oxygenation (ECMO), extended placement of electrodes for temporary pacing (for more than 3 days), prolonged central venous catheterization, re-sternotomy, number of blood and plasma transfusions, hyperhydration, the duration of tracheal intubation and stay in the intensive care unit.

Thus, there are still a number of challenges in prevention and treatment of sternal infection in pediatric cardiac surgery. Its elimination is difficult to achieve and requires a series of measures in the management of a patient from admission to hospital discharge. The level of surgical infection, along with rates of other serious complications and mortality, are objective indicators of the quality of patient care and medical care in general. The improvement of the surgical component, as well as some features of perioperative management in intensive care, anesthesia and cardiopulmonary bypass, will reduce the incidence of wound infection in pediatric cardiac surgery [18,28]. The aim of our study is to evaluate the efficiency of a developed method for preventing sternal infection in children after surgery for CHD.

## 2. Methods

A single-center retrospective cohort study was conducted from 2014 to 2021. To carry out this study, the treatment of 478 children with CHD including 201 newborns, was analyzed. The children were treated at Saint-Petersburg State Pediatric Medical University clinic. All patients had a complete median sternotomy as an operative approach. Our study was approved by the local ethics committee

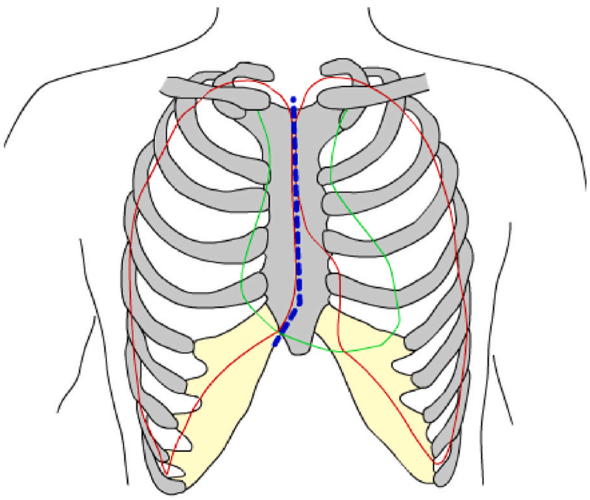

**Fig. 1.** Schematic representation of a complete longitudinal median sternotomy showing the anterior-frontal view of the chest. The dotted line indicates the optimal trajectory for sternum incision, which avoids the need to remove the xiphoid process.

at the St.-Petersburg State Pediatric Medical University (№29/05, August 07, 2023). Patients' parents gave their informed consent for the use of examination and treatment data in the scientific research.

The patients were assigned into 2 groups, taking into account the application of a developed algorithm for the prevention of sternal infection. Sternal surgical infection was divided into superficial (involving skin and/or subcutaneous tissue) and deep (involving the bone of the sternum and anterior mediastinum). If internal organs or spaces were involved in the infectious process, it was considered mediastinitis. In the first group, the prevention of wound infection was carried out using customary methodology. In the second group, according to a standardized protocol: 2nd generation cephalosporins (Cefuroxime) were administered parenterally and applied principles of general surgery for the prevention of surgical infection [2,7,20]. Antibacterial load 150 mg/kg/day in three doses. The first loading dose is administered intravenously at a rate of 50 mg/kg 2 h before surgery (before the skin incision; in case of emergency surgery - no later than 10 min before the skin incision). The second and third doses of 50 mg/kg are administered intravenously at intervals of 6–8 h after surgery. The course was 3–4 postoperative days.

The inclusion criteria for the study were: children under 1 year of age with CHD who underwent surgery involving a complete median sternotomy. Exclusion criteria were: age older than 1 year and/or other underlying disease (such as diaphragmatic hernia, esophageal atresia) children older than 1 year of age with surgically repaired CHD..

## 2.1. *Algorithm for the prevention of sternal infection*

Surgical measures.

- Sterile gloves and sterile surgical scrubs should be worn to prepare the surgical field.
- Alcohol-based antiseptic solutions are preferable for preparation of the surgical field. The solution is applied three times within 3–5 min intervals and the skin should be allowed to dry on its own.
- Gloves must be changed prior to skin incision.
- All soft tissues, as well as the periosteum of the sternum, must be dissected with a scalpel.
- Careful handling of instruments dealing with soft tissues is required [16]. Avoid devascularization and minimize the risks of impaired blood supply to the soft tissues, skin, and sternum [11,16].
- Electrocoagulation should be applied locally to stop bleeding from soft tissues and the periosteum.
- The sternotomy is carried out along the line of periosteum dissection, the xiphoid process does not need to be dissected and removed (Fig. 1).

- To stop bleeding from the sternum, wax is not recommended [20,28]. If it is used, it must be removed before sternal closure.
- When weaned from CPB, the wound must be washed with a warm solution of aminocaproic acid.
- Prior to suturing the wound, separate drainage of open cavities is performed including pericardium, pleural cavities and retrosternal space. (Fig. 2-A, B).
- The pericardial cavity must be completely separated from the retrosternal space with a T-shaped incision of the pericardium and mediastinal pleura.
- At the stage of hemostasis but before closure of the sternum, it is necessary to periodically cleanse the wound with a warm solution of NaCl 0.9 % and aminocaproic acid at each stage of suturing in order to remove small particles (such as fat residues, necrotic tissue) and prevent local fibrinolysis.

- Stabilization of the sternum is always performed using a wire ligature [18].

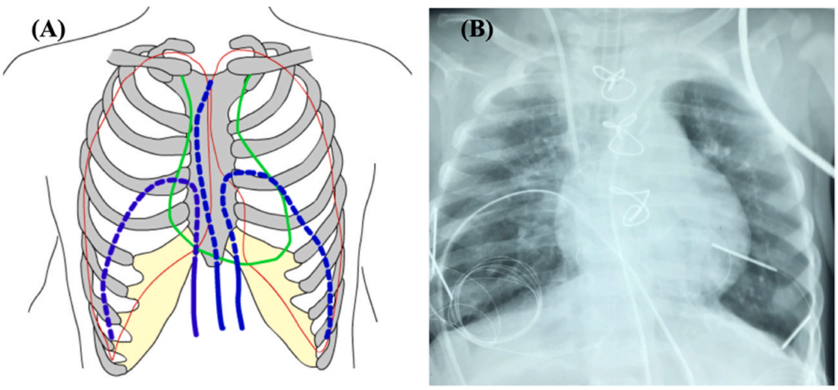


**Fig. 2.** Image of separate drainage of the pericardium, retrosternal space and pleural cavities. (A) Schematic representation of anterior-frontal view of the chest. The dotted line shows drains placed through the subxiphoid approach to the pericardium, retrosternal space, and pleural cavities. (B) Chest X-ray of a child after a full longitudinal stenotomy. sternum approximation was performed with stainless steel wire ligatures in 3 figure of eight-shaped sutures. The pericardium, retrosternal space and the right pleural cavity were drained through subxiphoid access.

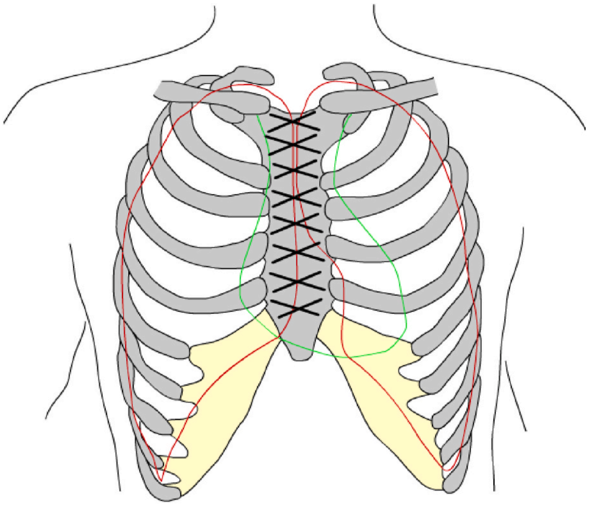

**Fig. 3.** Stabilization of the sternum with a wire ligatures. Schematic representation of the figure of eight-shaped sutures in the sternum with wire ligatures (one on the handle of the sternum, one around the articulation between the body and the handle and the rest on the body of the sternum.

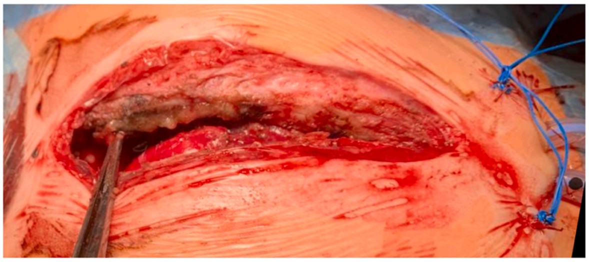

**Fig. 4.** View of the surgical wound. Antibiotic paste is smeared in the spongy substance of the sternum.

- During the primary access, it is necessary to form 1 or 2 eight-shaped sutures with wire ligatures: on the handle of the sternum, as well as around the articulation between the body and the handle of the sternum [20,28].
- When performing a resternotomy, it is necessary to make 3–5 eight-shaped sutures with wire ligatures (one on the handle of the sternum, another around the articulation between the body and the handle, the rest on the body of the sternum) (Fig. 2-B, 3).

- Before approximating the edges of the sternum, it is necessary to prepare a paste with an antibiotic (vancomycin 1 g mixed with 2–4 ml of 0.9 % NaCl) and the vancomycin paste should be applied directly to the cut edge of the sternum [28,29] (Fig. 4).
- Before suturing soft tissues, it is required to excise necrosis to viable tissues, especially in case of delayed suturing of the wound (the wound should bleed just a little) [11,16].
- The anterior chest wall muscles (fascio-muscular layer) must be sutured with separate sutures using absorbable suture material. In the case of delayed wound closure or in cases of a compromised wound (repeated access, high risk of impaired wound healing), it is necessary to use a non-absorbable polypropylene monofilament suture.
- After suturing the muscles of the anterior chest wall, the wound must be tamponaded with gauze wipes soaked in an antiseptic solution containing octenidine dihydrochloride and phenoxyethanol.
- Subcutaneous fat tissue should not be sutured in young children (under the age of 2–3) with a normosthenic body type.

- The fascio-muscular layer and subcutaneous fat must be sutured so that the thread and knots remain deep in the tissues (to prevent extrusion of the thread and knots) [11].

- While suturing soft tissues and skin, the sternotomy wound should be irrigated with an antibiotic solution (10 ml of a 0.9 % NaCl solution mixed with 0.5–1 g of vancomycin).
- Before applying an intradermal suture, the incisional film must be removed; the skin around the wound must be treated with alcohol-based antiseptic solutions.
- The skin closure is performed by applying an intradermal continuous suture with a fast-absorbing thread (preferably monofilament threads of the thinnest size, and the necessary strength) [16].

- If the wound is sealed with skin glue, a dressing is not required for 3–5 days. When closing the wound with a bandage on the first day, it is not recommended to change it or treat the wound with any solutions (provided the bandage remains dry) [3].
- When performing dressing changes, delicate handling of the wound is required with no touching or pressing it. Exposure to an alcohol-containing antiseptic solution (or a solution of octenidine dihydrochloride and phenoxyethanol) for several minutes is always necessary prior to covering the wound with a sterile dressing.
- Removal of drains from the pleural cavities, pericardial cavity and retrosternal space are performed if the discharge amount does not exceed 5 ml/kg per day.

Features of CPB and intensive care in the perioperative period.

- Catheterization of the central veins and peripheral arteries should fully comply with aseptic techniques (similar to the processing of the surgical field) [3].
- Central venous and arterial catheters should be removed as early as possible [18–20].
- It is essential to avoid hypernatremia and hyperhydration in the perioperative period. In all patients loop diuretics should be used to reduce fluid from the body with the goal to achieve zero/negative daily fluid balance [19].
- It is important to maintain target hemoglobin values in the perioperative period (more than 130 g/l for patients with biventricular hemodynamic physiology, more than 150 g/l for patients with a functional single ventricle hemodynamic physiology),
- Cardiac index must be kept above 2.2 l/min/m2,
- Ultrafiltration should be routinely applied during CPB [28].
- It is important to consider the patient's daily physiological need for energy, fluids and electrolytes. Basic infusion therapy should be calculated individually for each patient.
- It is necessary to strive for early patient mobilization in the postoperative period.

### 2.2. Statistical analysis

Differences between the 2 groups were compared using t-tests for the continuous variables with normal distributions, Mann–Whitney *U* test for abnormal distributions, and chi-square test for the qualitative data. To identify factors influencing the development of sternal infection after cardiac surgery using median sternotomy, we performed univariate and multivariate logistic regression analysis (the Expectation-maximization statistical algorithm is used) [30]. As a result of a review of the literature, the most significant risk factors for the development of sternal infection in children were identified. The criterion for inclusion of a risk factor in multiple analysis (with stepwise selection) was a level of statistical significance less than 0.05.

The analysis included 24 risk factors.

- preoperative: height, weight, sex, age at the time of surgery, cyanotic CHD, genetic abnormalities, type of CHD, risk according to the RACHS scale;
- intraoperative: type of operation, repeat sternotomy, delayed wound closure, use the cardiopulmonary bypass (CPB), level of the intraoperative hypothermia, duration of surgery and CPB, methodology of the prevention of wound infection;
- postoperative: use of peritoneal dialysis, postoperative acute renal failure, re-sternotomy in the early postoperative period, postoperative bleeding, the duration of mechanical ventilation, stay in the intensive care unit, use of a central venous catheter and hospitalization.

The correlation of each factor was determined using the Pearson $\chi^2$ test, before performing multiple analyses. Subsequently, to analyze the relationship of risk factors and the surgical outcomes, we performed multiple logistic regression analysis. Statistical processing was carried out using SPSS for Windows. The level of statistical significance was accepted as $p < 0.05$.

## 3. Results

Out of 478 children, the algorithm for the prevention of sternal infection was applied in 308 children (including 131 newborns). The mean age of patients at the time of surgery was 89.9 days (minimum - 0 days, maximum - 365 days). The mean weight was 4.7 kg (minimum - 1.2 kg, maximum - 60 kg). In total, sternal infection occurred in 16 cases (3.34 %) in both groups. Sternal infection developed in 2 children (0.65 %) of the first group (where the algorithm was applied) and in 14 children (8.2 %) of the second group (where the algorithm was not applied). Deep sternal infection developed in 1 patient in the first group (0.33 %) and in 5 patients in the second group (2.94 %). Sternal closure was delayed in 12 patients who developed sternal infection (1 patient in group 1 and 11 patients in group 2). In patients with deep sternal infection (6 people), the causative agent of wound infection was: in one case - *Klebsiella pneumoniae*, in another case - Staphylococcus epidermidis, *Pseudomonas aeruginosa*, in three more cases - Staphylococcus epidermidis, and in one more case - Acinetobacter baumanii. In patients with superficial sternal infection (10 people), the causative agent of the wound infection was: in two cases - Staphylococcus epidermidis, in other cases, seeding from the wound without growth of microorganisms. A more detailed description of the patients is presented in Table 1.

In the second group the incidence of sternal infection was significantly higher. While, the number of cases of delayed sternal closure (22.4 % vs. 19.4 %) and the number of newborns were approximately comparable (42.5 % vs. 41.2 %) between both groups. Cyanotic CHD (30.2 % versus 14.7 %) and previous sternotomy (15.3 % versus 9.5 %) were more frequent in the first group (Table 1).

**Table 1**
Demographic and clinical characteristics of the patients.

| Characteristics | Group 1[a] (n/%) | Group 2[a] (n/%) | p-value |
|---|---|---|---|
| Total number of patients | 308/478 (64 %) | 170/478 (36 %) | – |
| Demographic and clinical characteristics | | | |
| Height, cm | 54 [51; 62] | 54 [51; 64] | 0.635 |
| Weight, kg | 3,9 [3.2; 5.58] | 4 [3.3; 6] | 0.208 |
| Sex (male) | 175/56.8 | 99/58.2 | 0.764 |
| Age at the time of surgery, days | 43 [11; 154.5] | 52 [14; 147.75] | 0.385 |
| Neonate | 131/42.5 | 70/41.2 | – |
| Type of CHD: | | | 0.051 |
| - *CoA + Arch hypoplasia/IAA/VR* | 49/15.9 | 32/18.8 | |
| - *D-TGA/D-TGA + VSD* | 20/6.5 | 14/8.2 | |
| - *VSD/AVCD/TF* | 94/30.5 | 64/37.6 | |
| - *Pulmonary atresia/Truncus arteriosus* | 18/5.8 | 11/6.5 | |
| - *HLHS/Single ventricle* | 82/26.6 | 24/14.1 | |
| - *DORV* | 16/5.2 | 4/2.4 | |
| - *TAPVR* | 9/2.9 | 6/3.6 | |
| - *AV stenosis/ALCAPA* | 15/4.9 | 8/4.7 | |
| - *other* | 5/1.6 | 7/4.1 | |
| Type of operation: | | | 0.007 |
| - *Aortic arch reconstruction* | 29/9.4 | 19/11.2 | |
| - *Aortic arch reconstruction + other* | 28/9.1 | 16/9.5 | |
| - *Arterial switch* | 10/3.2 | 9/5.3 | |
| - *Arterial switch + VSD closure/Rastelli* | 12/3.9 | 6/3.6 | |
| - *ASD closure/atrioseptostomy* | 3/1 | 2/1.2 | |
| - *Valve plasty/replacement* | 9/2.9 | 5/2.9 | |
| - *Valve plasty/replacement + other* | 2/0.6 | 10/5.9 | |
| - *VSD or AVCD repair* | 68/22.1 | 43/25.4 | |
| - *Pacemaker implantation* | 3/1 | 0/0 | |
| - *RV-PA conduit impl./VR repair* | 7/2.3 | 11/6.5 | |
| - *Bilateral PA banding/PA banding* | 74/24 | 20/11.8 | |
| - *Norwood/DKS* | 17/5.5 | 6/3.6 | |
| - *Other correction of a single ventricle* | 27/8.8 | 13/7.7 | |
| - *TA/ALCAPA repair/PA unifocalisation* | 9/2.9 | 3/1.8 | |
| - *PV plasty/PV reimplantation* | 10/3.2 | 6/3.6 | |
| RACHS: | | | 0.461 |
| *1* | 6/1.9 | 1/0.6 | |
| *2* | 71/23.1 | 46/27.1 | |
| *3* | 129/41.9 | 67/39.4 | |
| *4* | 84/27.3 | 50/29.4 | |
| *5* | 0/0 | 0/0 | |
| *6* | 18/5.8 | 6/3.6 | |
| Peritoneal dialysis, overall | 48/15.6 | 42/24.7 | 0.015 |
| CPB, overall | 219/71.1 | 148/87.1 | <0.001 |
| Re-sternotomy (in the early PO), overall | 11/3.6 | 6/3.6 | 0.981 |
| Repeat_sternotomy, overall | 47/15.3 | 16/9.5 | 0.07 |
| Delayed sternal closure, overall | 69/22.4 | 33/19.4 | 0.445 |
| Postoperative bleeding, overall | 9/2.9 | 8/4.7 | 0.313 |
| Postoperative acute renal failure, overall | 23/7.5 | 19/11.2 | 0.174 |
| Duration of surgery, min | 240 [180; 320] | 330 [255; 440] | <0.001 |
| Duration of CPB, min | 80 [0; 120] | 140 [88.75; 222.5] | <0.001 |
| Duration of mechanical ventilation, days | 6 [4; 10] | 9 [6; 17] | <0.001 |
| ICU length of stay, days | 10 [6; 14] | 13.5 [10; 24] | <0.001 |
| Duration of the hospitalization, days | 20 [11; 27] | 26 [20; 38] | <0.001 |
| Duration of use of a CV catheter, days | 13 [9; 22.75] | 21.5 [13; 35.25] | <0.001 |
| Cyanotic CHD, overall | 93/30.2 | 25/14.7 | <0.001 |
| Genetic abnormalities, overall | 25/8.1 | 16/9.5 | 0.628 |
| Hypothermia intraoperative: | | | <0.001 |
| 14–20 degrees C | 3/1 | 19/11.2 | |
| 20–28 degrees C | 32/10.4 | 27/15.9 | |
| 28–34 degrees C | 34/11 | 32/18.8 | |
| Normothermic C | 239/77.6 | 92/54.1 | |
| Sternal infection: | | | <0.001 |
| - *overall* | 2/0.65 | 14/8.2 | |
| - *deep* | 1/0.33 | 5/2.9 | |
| - *superficial* | 1/0.33 | 9/5.3 | |

Notes: RACHS, risk adjustment for congenital heart surgery; CPB, cardio-pulmonary bypass; ICU, intensive care unit; CV, central venous; CHD, congenital heart disease; TF, tetralogy of Fallot; TAPVR, total anomalous pulmonary venous return; D-TGA, D-transposition of the great arteries; AV, aortic valve; ALCAPA, anomalous left coronary artery from the pulmonary artery; AVSD, atrioventricular septal defect; SV, single ventricle; DORV, double-outlet right ventricle; VSD, ventricular septal defect; HLHC, hypoplastic left heart complex; CoA, coarctation of the aorta; TA, truncus

arteriosus; IAA, interrupted aortic arch; VR, vascular ring; DKS, Damus–Kaye–Stansel procedure; RV, right ventricle; PA, pulmonary artery; PO, postoperative period.
[a] Group 1: using new algorithm; Group 2: without new algorithm.

Univariable analysis identified 16 variables associated with development of sternal infection (Table 2). Type of CHD (D-TGA or D-TGA + VSD – OR = 39.5, CI [9.708–160.716]; VSD or AVCD or TF – OR = 10.333, CI [3.159–33.8]; Pulmonary atresia or Truncus arteriosus – OR = 157, CI [21.978–1121.522]; DORV – OR = 14.143, CI [6.571–30.44]; TAPVR – OR = 19, CI [2.544–141.928]; other – OR = 22, CI [2.965–163.213]), type of operation (aortic arch reconstruction – OR = 11.6, CI [3.141–10.69]; arterial switch operation – OR = 10, CI [3.578–27.949]; arterial switch operation with VSD closure or Rastelli operation – OR = 8.5, CI [1.964–36.79]; ASD closure or atrioseptostomy – OR = 17, CI [2.262–127.74]; VSD or AVCD repair – OR = 11, CI [1.42–85.201]; bilateral PA banding or banding of the main PA – OR = 17, CI [2.262–127.74]; Norwood or DKS operation – OR = 46, CI [11.333–186.705]; other correction of a «single ventricle» – OR = 4.75, CI [1.616–13.962]; truncus arteriosus or ALCAPA repair or PA unifocalisation – OR = 39, CI [5.358–283.864]), RACHS (№ 1 – OR = 4.29, CI [1.38–12.917]; № 3 – OR = 23.2, CI [2.465–218.383]; № 4 – OR = 6.333, CI [1.648–24.344]; № 6 – OR = 5.16, CI [1.277–20.854]), use a peritoneal dialysis in the postoperative period (OR = 10.666, CI [3.606–31.55]), re-sternotomy in the early postoperative period (OR = 11.513, CI [3.27–40.538]), delayed sternal closure (OR = 12.4, CI [3.908–39.349]), postoperative bleeding (OR = 7.385, CI [1.889–28.871]), postoperative acute renal failure (OR = 12.559, CI [4.437–35.544]) associated with increased odds of developing of sternal infection.

Conversely, type of CHD (coarctation of the aorta + Arch hypoplasia or interrupted aortic arch or vascular ring – OR = 0.143, CI [0.909–1.737]), duration of surgery (OR = 0.991, CI [0.988–0.995]), duration of CPB (OR = 0.991, CI [0.988–0.995]), duration of mechanical ventilation (OR = 0.962, CI [0.934–0.992]), ICU length of stay (OR = 0.967, CI [0.946–0.988]), duration of the hospitalization (OR = 0.964, CI [0.944–0.984]), duration of use of a CV catheter (OR = 0.964, CI [0.946–0.983]), use of hypothermia during surgery (14-20$^{o}$ C – OR = 0.042, CI [0.261–0.632], 20-28$^{o}$ C – OR = 0.069, CI [0.017–0.279], 28-34$^{o}$ C – OR = 0.166, CI [0.046–0.591]) and application of the algorithm (OR = 0.072, CI [0.016–0.321]) associated with lower odds of developing of sternal infection.

Multivariable regression analysis was used to determine the complex effect of risk factors on the probability of developing sternal infection in the studied category of patients (Table 3). As a result, such independently perioperative risk factors as postoperative re-sternotomy (OR = 23.315, CI [4.231–128.459]), delayed chest closure (OR = 9.087, CI [2.116–39.023]), and the development of acute renal failure (OR = 5.322, CI [1.334–21.231]) led to a statistically significant increase in the probability of complications. Application of the algorithm for the prevention of sternal infection resulted in a significant risk reduction, by ~31 times (OR = 0.032, CI [0.005–0.205]).

## 4. Discussion

Despite literature that the existing methods for prevention of sternal infection in cardiac surgery patients can reduce its frequency to varying degrees: the incidence of deep sternal infection in the form of osteomyelitis of the sternum and mediastinitis remains high and ranges from 0.5 % to 14 % [4,9,20]. Prevention of sternal infection is multifactorial at each stage of patient treatment, including the roles of preoperative and perioperative management, and intensive care unit care. Therefore, we took into account all possible risk factors. The method of prevention of sternal infection was developed on the basis of the stages of treatment and pathogenesis of wound infection and represents a set of measures aimed at improving the surgical component, as well as some features of perioperative management in intensive care, anesthesia and CPB.

Obviously, measures to prevent the development of sternal infection begin from the moment the patient enters the hospital, because preparation for surgery largely depends on therapeutic measures. For example, preoperative preparation often does not take into account the daily physiological need for fluids, the daily fluid balance, which can increase the risk of developing a surgical infection. The pathophysiology of CHD with hypervolemia of the pulmonary circulation may lead to the development of heart failure and downstream organ dysfunction, fluid retention and progression of peripheral edema. As a result of the redistribution of fluid into the interstitial space, due to many pathophysiological processes, wound healing processes are also disrupted, and the risk of infectious complications increases. This effect is enhanced by the consequences of CPB: the barrier function of inflammation is impaired due to the appearance of inflammatory mediators and pro-inflammatory cytokines in the systemic circulation, with systemic manifestations of inflammation [31]. There are several effective ways to reduce the severity of this condition. The main ones are the "aggressive" use of diuretics in the perioperative period and the use of ultrafiltration (UF) during CPB. In addition to removing inflammatory mediators and cytokines from the blood, the use of UF is an effective way to control the volume of circulating blood by regulating the balance between the injected and excreted fluid [31–33]. As a result of analyzing patient treatment histories, we identified a high incidence of these risk factors and included them as necessary measures to prevent sternal infection.

Furthermore, in addition to perfusion and anesthetic measures during surgery, great attention should be paid to surgical procedures. The negative effect of surgical interventions on the microcirculation of soft tissues was assessed. Risk factors for blood supply to the sternum and the development of its instability in the postoperative period were identified. The use of antiseptics and antibiotics, and drainage of the surgical wound, were optimized. For example, as a result of the use of electrocoagulation to stop bleeding from soft tissues and the sternum, the formation of necrosis was noted, especially in the skin and subcutaneous fat. This obviously led to a significant disruption of the blood supply to the edges of the wound and its healing, therefore some steps were taken to prevent these consequences. It should be noted that such simple manipulations as periodically changing gloves during preparation for surgery, using local electrocoagulation, minimizing the use of bone wax, using a wire ligature for sternum reapproximation, local use of an antibiotic,

**Table 2**
Analysis of factors associated with development of sternal infection (univariable regression analysis).

| Risk factors | OR [CI 95 %] | p-value[a] |
|---|---|---|
| Height | 1.037 [0.982–1.094] | 0.189 |
| Weight | 1.208 [0.867–1.683] | 0.264 |
| Sex | 1.357 [0.501–3.679] | 0.548 |
| Age at the time of surgery | 1.005 [0.988–1.012] | 0.177 |
| Type of CHD: | | |
| - *CoA + Arch hypoplasia/IAA/VR* | 0.143 [0.909–1.737] | <0.001 |
| - *D-TGA/D-TGA + VSD* | 39.5 [9.708–160.716] | <0.001 |
| - *VSD/AVCD/TF* | 10.333 [3.159–33.8] | <0.001 |
| - *Pulmonary atresia/Truncus arteriosus* | 157 [21.978–1121.522] | <0.001 |
| - *HLHS/Single ventricle* | 1,615e+9 [0- ∞] | 0.998 |
| - *DORV* | 14.143 [6.571–30.44] | <0.001 |
| - *TAPVR* | 19 [2.544–141.928] | 0.004 |
| - *AV stenosis/ALCAPA* | 1,615e+9 [0- ∞] | 0.998 |
| - *other* | 22 [2.965–163.213] | 0.003 |
| Type of operation: | | |
| - *Aortic arch reconstruction* | 11.6 [3.141–10.69] | <0.001 |
| - *Aortic arch reconstruction + other* | 1,615e+9 [0- ∞] | 0.997 |
| - *Arterial switch* | 10 [3.578–27.949] | <0.001 |
| - *Arterial switch + VSD closure/Rastelli* | 8.5 [1.964–36.79] | 0.004 |
| - *ASD closure/atrioseptostomy* | 17 [2.262–127.74] | 0.006 |
| - *Valve plasty/replacement* | 1,615e+9 [0- ∞] | 0.999 |
| - *Valve plasty/replacement + other* | 1,615e+9 [0- ∞] | 0.998 |
| - *VSD or AVCD repair* | 11 [1.42–85.201] | 0.022 |
| - *Pacemaker implantation* | 1,615e+9 [0- ∞] | 0.997 |
| - *RV-PA conduit impl./VR repair* | 1,615e+9 [0- ∞] | 0.998 |
| - *Bilateral PA banding/PA banding* | 17 [2.262–127.74] | 0.006 |
| - *Norwood/DKS* | 46 [11.333–186.705] | <0.001 |
| - *Other correction of a single ventricle* | 4.75 [1.616–13.962] | 0.005 |
| - *TA/ALCAPA repair/PA unifocalisation* | 39 [5.358–283.864] | <0.001 |
| - *PV plasty/PV reimplantation* | 1,615e+9 [0- ∞] | 0.999 |
| RACHS: | | |
| *1* | 4.29 [1.38–12.917] | 0.027 |
| *2* | 323e+6 [0- ∞] | 0.999 |
| *3* | 23.2 [2.465–218.383] | 0.006 |
| *4* | 6.333 [1.648–24.344] | 0.007 |
| *5* | – | – |
| *6* | 5.16 [1.277–20.854] | 0.021 |
| Peritoneal dialysis | 10.666 [3.606–31.55] | <0.001 |
| CPB | 2.161 [0.484–9.659] | 0.313 |
| Re-sternotomy (in the early PO) | 11.513 [3.27–40.538] | <0.001 |
| Repeat sternotomy | 0.939 [0.208–4.234] | 0.935 |
| Delayed sternal closure | 12.4 [3.908–39.349] | <0.001 |
| Postoperative bleeding | 7.385 [1.889–28.871] | 0.004 |
| Postoperative acute renal failure | 12.559 [4.437–35.544] | <0.001 |
| Duration of surgery | 0.991 [0.988–0.995] | <0.001 |
| Duration of CPB | 0.991 [0.988–0.995] | <0.001 |
| Duration of mechanical vent. | 0.962 [0.934–0.992] | 0.013 |
| ICU length of stay | 0.967 [0.946–0.988] | 0.002 |
| Duration of the hospitalization | 0.964 [0.944–0.984] | <0.001 |
| Duration of use of a CV catheter | 0.964 [0.946–0.983] | <0.001 |
| Cyanotic CHD | 1.875 [0.667–5.274] | 0.234 |
| Genetic abnormalities | 1.549 [0.34–7.066] | 0.572 |
| Hypothermia intraoperative: | | |
| 14–20 degrees C | 0.042 [0.261–0.632] | 0.001 |
| 20–28 degrees C | 0.069 [0.017–0.279] | <0.001 |
| 28–34 degrees C | 0.166 [0.046–0.591] | 0.006 |
| Normothermic C | 0.491 [0.093–2.585] | 0.401 |
| Application of the algorithm | 0.072 [0.016–0.321] | 0.001 |

Notes.
RACHS, risk adjustment for congenital heart surgery; CPB, cardio-pulmonary bypass; ICU, intensive care unit; CV, central venous; CHD, congenital heart disease; TF, tetralogy of Fallot; TAPVR, total anomalous pulmonary venous return; D-TGA, D-transposition of the great arteries; AV, aortic valve; ALCAPA, anomalous left coronary artery from the pulmonary artery; AVSD, atrioventricular septal defect; SV, single ventricle; DORV, double-outlet right ventricle; VSD, ventricular septal defect; HLHC, hypoplastic left heart complex; CoA, coarctation of the aorta; TA, truncus arteriosus; IAA, interrupted aortic arch; VR, vascular ring; DKS, Damus–Kaye–Stansel procedure; RV, right ventricle; PA, pulmonary artery; PO, postoperative period.

[a] Statistically significant value ($p < 0.05$). OR, odds ratio; CI, confidence interval.

**Table 3**
Multivariable logistic regression model of factors associated with development of sternal infection.

| Risk factors | OR [CI 95 %] | p-value[a] |
|---|---|---|
| Re-sternotomy (in the early postoperative period) | 23.315 [4.231–128.459] | <0.001 |
| Delayed sternal closure | 9.087 [2.116–39.023] | 0.003 |
| Postoperative acute renal failure | 5.322 [1.334–21.231] | 0.018 |
| Application of the algorithm | 0.032 [0.005–0.205] | <0.001 |

Notes.
[a] Statistically significant value ($p < 0.05$). OR, odds ratio; CI, confidence interval.

excision of necrotic and compromised skin areas (especially when suturing the wound in cases of delayed sternum closure) and other algorithm steps which have not previously been routinely used. The inclusion of these steps in all patients complemented the number of mandatory actions of the surgeon and made it possible to significantly reduce the risks and occurrence of sternal infection among patients in group 1. By minimizing the risks of tissue ischemia and topical application of an antibiotic in the wound, we were able to significantly reduce the incidence of sternal infection, even in high risk patients. This was noted by previous authors, and such measures were successfully applied by them [34–36]. It should be noted that some authors noted the development of acute renal dysfunction, in combination with a high comorbidity index and intravenous administration of vancomycin [37]. In that study the systemic use of the antibiotic increased the chances of developing acute renal failure by 2.44 times, and the local use by 1.5 times. Thus, parenteral administration of antibiotics has a different effect on kidney and probably liver function. Of course, this allows you to achieve high levels of its concentration in the blood and this clearly reduces the risk of developing a wound infection. However, it can also negatively affect liver and kidney function. In addition, in the presence of hypoxemia and peripheral vasoconstriction, it is difficult to create a high concentration of most substances in the wound, due aseptic inflammation and edema in the area of surgical injury. Moreover, the delivery of antibiotics to the wound also depends on the quality of systemic perfusion. When antibiotics are applied topically in a wound, they bind to the fibrin clot where they can be effective against contaminating organisms. However, antibiotics do not diffuse well into the fibrin clot, reducing their effectiveness.

In our technique, much attention is paid to delivering oxygen to the tissues in the area of the sternotomy wound. As a rule, healing processes proceed most quickly and local immunity is strongest at a high level of oxygen in the wound tissues. This is achieved mainly by maintaining normal perfusion of the damaged tissue area. Wound tissue oxygenation is complex and depends on the interaction of several factors: tissue perfusion, oxygen tension in arterial blood, hemoglobin dissociation conditions, diffusion, and local oxygen consumption. Delivery of oxygen to the wound depends on the contractile function of the heart, the degree of vasoconstriction and arterial partial pressure of oxygen. This aspect is very important in the physiology of wound healing due to the fact that most of the oxygen consumed in wounds is used to produce oxidants for killing bacteria, as well as for collagen synthesis, angiogenesis and epithelialization [16,19]. Taking this into account, we consider it necessary to ensure normal perfusion of peripheral tissues, avoid arterial hypoxemia, maintain target hemoglobin values, and minimize the risks of impaired blood supply and tissue devascularization in the wound area in the perioperative period. Such measures in our algorithm included optimization of surgical actions and intensive care: locally applied electrocoagulation, avoiding the use of bone wax, refraining from excising the xiphoid process, excision of areas of skin necrosis, suturing soft tissues with separate sutures, addressing hypernatremia and overhydration in the perioperative period, routinely using the ultrafiltration method, maintaining target hemoglobin values in the perioperative period and early patient mobilization. It is especially important to adhere to these concepts in patients with cyanotic CHD and the hemodynamics of a functionally single ventricle heart. In a study by Allpress et al., in contrast to these concepts, the multivariate analysis did not find a strong relationship between perioperative hypoxemia and tissue ischemia and an increased risk of sternal infection. But it should be noted that study was conducted with a small sample of patients (141) and an older age group (up to 13 years) [25].

Analyzing the possible reasons for the development of a surgical infection, some authors consider that most medical personnel, including surgeons, do not have standardized concepts for caring for a sternal wound in children after heart surgery [17]. The authors formulated an algorithm for wound care. The introduction of the proposed algorithm into practice and the formed wound care assessment map made it possible to significantly reduce the incidence of sternal infection.

Ben-Ami et al., in a large study identified young age, cyanotic CHD and the duration of central venous catheterization as the most important risk factors for developing sternal infection [5]. Similar results were obtained in a study by Allpress et al. [25], where age less than 28 days was the most significant risk factor for the development of sternotomy wound infection after cardiac surgery. The results of another scientific work determined that the age of patients from 1 to 10 years as the most significant factor [38]. According to the univariate and multiple analyses in our study, ages under 1 year old and cyanotic CHD were not statistically significant risk factors. The duration of central venous catheterization had a statistically significant effect on the development of sternal infection in our study (univariate regression analysis). A more important result was the determination of the complex influence of perioperative factors in multiple analyses. According to our data, predictors of sternal infection were re-sternotomy in the early postoperative period (OR = 23.315, $p < 0.001$), delayed chest closure (OR = 9.087, $p = 0.003$), acute renal failure in the postoperative period (OR = 5.322, $p = 0.018$). Most importantly, application of a developed algorithm for the prevention of sternal infection (OR = 0.032, $p < 0.001$) improved results by more than 30 fold. As a result of this approach to the prevention of sternal infection, it was possible to significantly reduce its frequency from 8.2 % to 0.65 %, which improved overall patient outcomes and subsequently reduced the cost of treatment.

## 5. Conclusion

The proposed algorithm for the prevention of sternal infection has significantly reduced the incidence of sternal infection after cardiac surgery in children under 1 year of age. In patients at moderate to high risk for surgical site infection, surgeons are able to improve wound healing and prevent wound infections with simple, inexpensive, and readily available tools and techniques. Aseptic surgical techniques, local use of antibiotics, prevention of peripheral vasoconstriction, and maintenance of normal oxygen delivery values are key. In the postoperative period, the focus should be on an individualized approach to intensive care.

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## Data availability statement

Data included in article/supp. material/referenced in article. The raw data used in this study are available from the corresponding author upon reasonable request.

## Ethics statement

This study was approved by the local ethics committee at the St.-Petersburg State Pediatric Medical University (№29/05, August 07, 2023). The parents of the child, whose data or images are included in this publication, provided consent for all images and clinical data and other data included in the manuscript to be published.

## CRediT authorship contribution statement

**V.V. Suvorov:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **V.V. Zaitsev:** Writing – review & editing, Validation, Investigation. **E.M. Gvozd:** Writing – review & editing, Formal analysis, Data curation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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