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Hearing impairment following surgically repaired congenital heart disease in children: a prospective study

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ABSTRACT

Objectives To determine the prevalence of sensorineural hearing loss (SNHL) in children who underwent congenital cardiac surgery (CCS) by using a pre- and postoperative hearing test, a conventional audiometry, an extended high-frequency audiometry (HFA) or auditory steady-state response (ASSR), and distortion-product otoacoustic emissions (DPOAE).

Study design This prospective study enrolled children with CCS in Siriraj Hospital, Thailand, between 2019 and 2023. Conventional audiometry including HFA or ASSR and DPOAE were performed pre- and postoperatively. The patients with bilateral abnormal hearing loss or an incomplete examination were excluded. Collected data included: demographics, cardiac surgery and ototoxic medication. Prevalence of SNHL by conventional audiometry and subclinical hearing impairment by HFA or DPOAE were ascertained, and risks were analysed.

Results Ninety-eight patients were eligible for the study. The median age (IQR) was 5.3 (1.5–9.6) years. Fifteen patients (15.3%) had univentricular hearts. The preoperative audiologic test was performed 1 day prior to the CCS. The postoperative test was performed at a median of 4.4 (IQR: 2.7–8.0) months postoperatively. Preoperative unilateral hearing impairments were reported in 17 patients (17.3%). Postoperatively, four patients (4.1%) showed significantly abnormal audiogram (> 25 dB) or 15 dB shift at 250–8000 Hz consistent to a new SNHL. Subclinical hearing impairment by HFA was affected in 10 patients (10.2%). Thirty-three patients (33.6%) had abnormal DPOAE exclusively. Therefore, new SNHL, including subclinical hearing loss, revealed a prevalence of ototoxicity up to 47.9%. Age <1 year at surgery was the independent risk of postoperative SNHL (adjusted OR 18.5, 95% CI 1.2 to 293.8, p=0.04).

Conclusion Routine post-CCS audiological surveillance especially CCS in infancy is recommended for early recognition and timely management based on the 43.8% subclinical and the 4.1% SNHL that was found in this study.

Trial registration number TCTR20200421001.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ The incidence of sensorineural hearing loss (SNHL) increased in adults following bypass surgery. Data of SNHL in children following congenital cardiac surgery (CCS) are limited. Based on a few of studies, the incidence of hearing loss was 65.6 per 1000 operations. However, no preoperative audiologic assessments were conducted, and co-occurring SNHL and CHD prior to CCS could have been confounded in the data.

WHAT THIS STUDY ADDS

⇒ A prevalence of postoperative SNHL of 4.1% by using conventional audiometry and subclinical SNHL was detected by HFA and DPOAE of 43.8%. High-frequency hearing impairment is mostly affected. The age <1 year at surgery was the significant risk of postoperative SNHL (adjusted OR 18.5, 95% CI 1.2 to 293.8, p=0.04).

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ The findings from the study suggest that children undergoing CCS may be at risk for SNHL, potentially increasing risk of neurodevelopmental difficulties. Post-CCS audiological surveillance is recommended for early recognition and timely management particularly in infants under 1 year old.

INTRODUCTION

Congenital heart disease (CHD) is a common birth defect worldwide affecting millions of live births per year.[1] Dramatic improvements in surgical correction and medical treatment have led to an increase in the survival of children with CHD into adulthood, though a considerable percentage of the survivors continue to have a neurodevelopmental disability. Hearing loss is one of potential problems that can limit CHD patients from developing speech capabilities and social

skills.[2] The sensorineural hearing loss (SNHL) in CHD has been recognised with a plausible mechanism for their co-occurrence involving developmental dysregulation of the inner ear and heart and genetic aetiologies.[3] There were some risk indicators for paediatric hearing loss possibly associated with the CHD care and surgery, such as the prolonged intensive care, use of an extracorporeal membrane oxygenator, using assisted ventilation, exposure to ototoxic medications (aminoglycosides) or loop diuretics (furosemide).[4] Furosemide, which are commonly used to treat CHD patients after cardiac surgery, may induce pathological ischaemic damage or oedema to the stria vascularis and cochlear lateral wall that occurs with the hearing impairment.[5] The ototoxic effects of high dosage intravenous furosemide and kidney injury have been reported from prior studies.[6 7]

The greater incidence of SNHL in adult patients after coronary bypass surgery, compared with the incidence in the normal population, has been reported. Possible attributing factors include: thromboembolic phenomena, perfusion failure, hypothermia, ototoxic drug use and central nervous system injury. Nevertheless, no proven aetiologies have been established.[8 9] Data for paediatric patients following congenital cardiac surgery (CCS) and SNHL are limited and unique.[10] Robertson reported the prevalence of permanent hearing loss (PHL) after Norwood right ventricular-pulmonary artery shunt for hypoplastic left heart syndrome (HLHS) to be 28.6% at the 4-year-old audiologic examination.[11] Grasty *et al* reported that 6.9% of the 4-year-old survivors of CCS in infancy had SNHL, and 2.3% had indeterminate hearing loss,[12] which is in accordance with Bork and colleagues reported prevalence of PHL (5.9%) after complex cardiac surgery at less than 6 weeks of age at the 4-year-old audiologic examination.[13] Gopineti *et al* estimated the prevalence of hearing loss to be 11.6% for 172 palliated/repaired CHD patients.[14] The incidence of hearing loss across these studies was 97 out of 1342 (65.6 per 1000 operations).[10] However, no preoperative audiologic assessments were conducted for the paediatric patients in these studies, and co-occurring SNHL and CHD prior to CCS could have been confounded in the data.

Therefore, we conducted this prospective study to: (1) investigate the changes between pre- and postoperative hearing thresholds, measured by conventional audiometry with extended high-frequency audiometry (HFA) or auditory steady-state response (ASSR) in uncooperative children and distortion-product otoacoustic emissions (DPOAE) in paediatric patients undergoing CCS to ascertain the prevalence of SNHL in this population and (2) identify the risk factors for SNHL. Importantly, the audiology screening was scheduled pre- and postoperation to ascertain whether the patients had abnormal hearing or not prior CCS. We hypothesised that paediatric patients who underwent CCS may have a reduced hearing threshold, compared with their preoperation threshold, especially in patients who received high dosage of furosemide or moderate hypothermic cardiopulmonary bypass or underwent a high complexity operation or had single ventricle repair.

MATERIALS AND METHODS

Study population and study design

This prospective observational study was approved by the Siriraj Institutional Review Board, Faculty of Medicine, Siriraj Hospital, Mahidol University (Study number

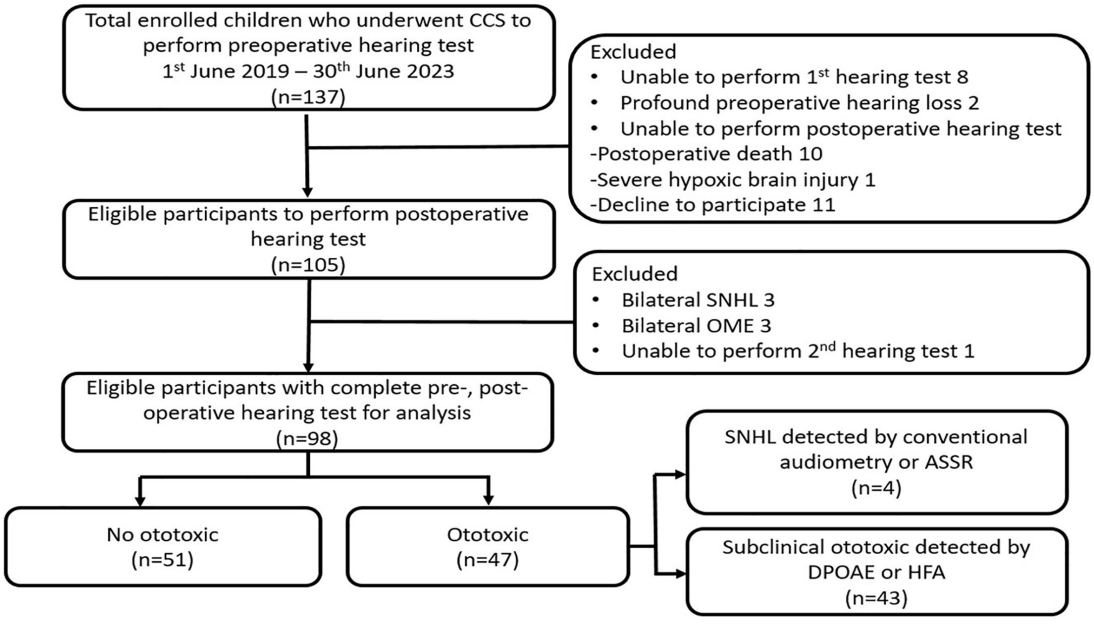

Figure 1 Flow diagram of the study (n=98) (ASSR, auditory steady-state response; CCS, congenital cardiac surgery; DPOAE, distortion-product otoacoustic emission; HFA, extended high-frequency audiometry; OME, otitis media with effusion; SNHL, sensorineural hearing loss.

Table 1 Baseline characteristics (n=98)

	Total (n=98)	Postoperative SNHL (n=4)	Postoperative subclinical hearing loss (n=43)	No postoperative hearing loss (n=51)	P value among three groups
Age at surgery (years)	5.3 (1.5–9.6)	0.8 (0.6–5.2)	6.9 (2.0–9.9)	4.8 (1.5–8.8)	0.415
Age <1 year at surgery	18 (18.4%)	3 (75.0%)	4 (9.3%)	11 (21.5%)	0.004*
Male gender	55 (56.0%)	2 (50.0%)	26 (60.5%)	27 (52.9%)	0.593
Weight (kg)	19.9±14.4	11.0±9.8	22.1±15.3	18.7±13.7	0.237
Height (cm)	106.7±29.6	81.7±35.7	112.7±28.7	103.5±29.0	0.073
Diagnosis					
Cyanotic heart disease	36 (36.7%)	0	18 (41.9%)	18 (35.3%)	0.240
Presence of syndromic disorder	9 (9.2%)	1 (25.0%)	4 (9.3%)	4 (7.8%)	0.519
Down syndrome	4 (44.4%)	1 (100%)	0 (0%)	3 (75%)	
DiGeorge syndrome	1 (11.1%)	0 (0%)	1 (25%)	0 (0%)	
Others	4 (44.4%)	0 (0%)	3 (75%)	1 (25%)	
History of preterm	8 (8.2%)	1 (25.0%)	2 (4.7%)	5 (9.8%)	0.301
Previous cardiovascular surgery	24 (24.5%)	0 (0%)	14 (32.6%)	10 (19.6%)	0.177
Preoperative usage of furosemide	37 (37.8%)	3 (75%)	18 (41.9%)	16 (31.4%)	0.169
Preoperative unilateral abnormal hearing on HFA/ASSR	17 (17.3%)	1 (25%)	8 (18.6%)	8 (15.7%)	0.857
Preoperative unilateral SNHL	9 (9.2%)	1 (25%)	3 (7.0%)	5 (9.8%)	0.478
Operative factors					
Single ventricular repair	15 (15.3%)	0 (0%)	10 (23.3%)	5 (9.8%)	0.135
Procedure STAT mortality score	0.4 (0.2–0.6)	0.6 (0.3–0.7)	0.5 (0.2–0.6)	0.3 (0.2–0.6)	0.155
Procedure STAT categories 4–5	11 (11.2%)	0 (0%)	5 (11.6%)	6 (11.8%)	0.768
Procedure Aristotle Basic Complexity Score	7.0±2.0	6.6±0.8	7.1±1.9	6.9±2.1	0.841
CPB time (min)	100.0±63.5	55.5±53.7	100.1±61.8	103.5±65.3	0.350
Aortic cross clamp time (min)	56.4±51.3	45.2±39.8	47.1±46.7	65.1±54.9	0.217
Operative time (min)	170.5±77.1	123.7±58.5	171.8±83.6	173.0±72.5	0.468
Minimal temperature in CPB (°C)	31.4±2.8	32.2±3.7	31.3±2.9	31.4±2.7	0.804
Moderate hypothermic CPB	17 (17.3%)	1 (25.0%)	7 (16.3%)	9 (17.6%)	0.710
Postoperative factors					
Postoperative vancomycin	4 (4.1%)	0 (0%)	1 (2.3%)	3 (5.9%)	0.628
Postoperative maximal vasoactive inotropic score	7.8 (23.5)	17.0±18.8	15.9±21.9	18.3±24.1	0.874

Continued

Table 1 Continued

	Total (n=98)	Postoperative SNHL (n=4)	Postoperative subclinical hearing loss (n=43)	No postoperative hearing loss (n=51)	P value among three groups
Postoperative usage of dopamine >4 mcg/kg/min	25 (25.5%)	4 (100%)	7 (16.3%)	14 (27.5%)	0.001*
Postoperative cumulative furosemide in 72 hours (mg)	67.4±36.2	42.9±18.7	75.2±42.8	62.7±29.2	0.093
Postoperative maximal furosemide dosage (mg/kg/day)	3.4±2.5	3.1±1.6	2.9±1.7	3.8±3.1	0.270
Postoperative maximal furosemide dosage >4 mg/kg/day	27 (27.6%)	1 (25.0%)	10 (23.3%)	16 (32.0%)	0.639
Route of maximal dose furosemide ► Intravenous drip ► Intravenous bolus ► Oral and intravenous bolus ► Oral ► Intravenous bolus and intravenous drip	0 (0%) 44 (44.9%) 28 (28.6%) 19 (19.4) 6 (6.1)	0 (0%) 3 (75%) 1 (25%) 0 (0%) 0 (0%)	0 (0%) 19 (44.2%) 12 (27.9%) 10 (23.3%) 2 (4.7%)	0 (0%) 22 (44%) 15 (30%) 8 (18%) 4 (8%)	0.847
Duration of intravenous furosemide (days)	3.9±2.1	3.2±0.9	3.7±2.3	4.1±2.0	0.641
Postoperative maximal creatinine level (mg/dL)	0.4±0.1	0.3±0.1	0.5±0.2	0.4±0.1	0.082
Oxygen saturation before discharge home (%)	96.8±4.6	98.2±1.3	95.9±5.4	97.4±3.8	0.219
Hospital length of stay (days)	8.0±4.9	9.5±7.7	7.5±3.7	8.4±5.5	0.577
Time interval from surgery to second audiologic examination (months)	4.4 (2.7–8.0)	4.3 (3.1–6.9)	3.6 (1.8–6.6)	5.3 (2.9–9.0)	0.176

Data presented as n (%), mean±SD and median (IQR p25–p75).
*Statistically significant at p value among three groups <0.05.
ASSR, auditory steady-state responses; CPB, cardiopulmonary bypass; HFA, extended high-frequency audiometry; SNHL, sensorineural hearing loss; STAT, The Society of Thoracic Surgeons Congenital Heart Surgery.

075/2562 (EC2), COA: Si 382/2019). The study period was June 2019 to June 2023 when 1357 paediatric patients (age <18 years) underwent CCS in Siriraj Hospital, Thailand. A total of 137 children were enrolled in the study and had preoperative hearing assessments. Informed consents were obtained from the parents or legal guardians. The exclusion criteria were: (1) preterm at the time of surgery, (2) underlying chronic renal insufficiency, (3) inability to complete the audiologic examination, (4) presence of bilateral conductive hearing loss such as otitis media with effusion (OME) or (5) presence of bilateral SNHL. Finally, 98 children were eligible for the analysis (figure 1).

Demographic data, including age, gender, weight, height, CHD diagnosis, presence of syndromic disorders, previous cardiac surgery, preoperative furosemide usage and preoperative unilateral abnormal hearing on HFA/ASSR, and intraoperative data, including type of operation, single ventricular repair and complexity of the surgical procedure using Aristotle Basic Complexity score,

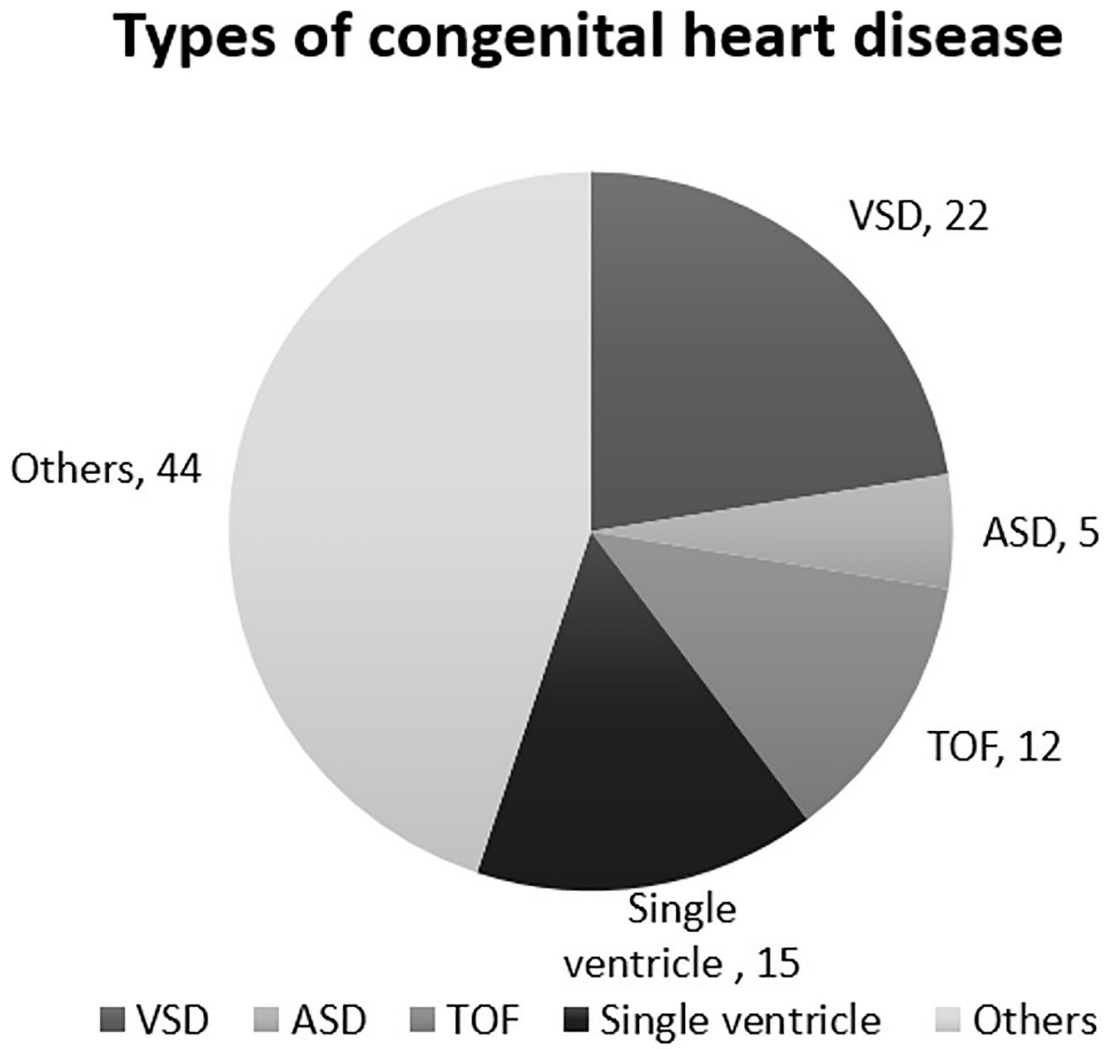

Figure 2 Types of congenital heart disease (n=98). ASD, atrial septal defect; TOF, tetralogy of Fallot; VSD, ventricular septal defect.

The Society of Thoracic Surgeons-European Association for Cardio-Thoracic Surgery (STAT) mortality score, operative time, cardiopulmonary bypass (CPB) time, aortic cross clamp time, minimal temperature during CPB and extracorporeal membrane oxygenator (ECMO) usage were collected. The postoperative parameters which included duration of ventilator usage, maximal vasoactive inotropic score, cumulative furosemide usage in 72 hours (mg), maximal furosemide dosage (mg/kg/day), route of maximal dose furosemide, duration of intravenous furosemide, maximal creatinine level (mg/dL) and hospital length of stay (LOS) were explored.

Audiological assessment and outcome measure

The first and second audiologic examinations were scheduled pre- and postoperatively, respectively. The preoperative test was performed 1 day prior to the CCS. The postoperative test was performed at a median of 4.4 (IQR: 2.7–8.0) months postoperatively according to the COVID-19 pandemic. Each audiologic assessment was performed in the Otorhinolaryngology department using age appropriate and standard techniques. For hearing thresholds, young children and developmentally delayed children were tested by ASSRs, while cooperative older children underwent behavioural audiological assessment using pure tone audiometry. Beyond the conventional audiometry (0.25–8 kHz), we tested in the HFA (9–20 kHz) or extra high-frequency audiometry (EFA) to cover HF-SNHL, which we postulated to occur post-CCS. The SNHL from conventional audiometry in the study was defined according to the 1991 WHO's grading of hearing impairment and current Common Terminology Criteria for Adverse Events.[2 15–17] Hearing loss at any particular frequency (0.25–8 kHz) was defined as a dropped response of more than a 25-decibel hearing level (dB HL) in either ear. The degree of hearing loss was classified as mild (grade 1), 26–40; moderate (grade 2), 41–60; severe (grade 3), 61–80; and profound/deafness (grade 4), ≥ 81 dB HL. In addition, a change of 15 dB or more, in either ear, at any test frequency from 500 Hz to 6000 Hz determined by pre- and postoperative audiometry was also

defined as SNHL according to National Institute of Occupational Safety and Health recommended definition of a standard threshold shift in SNHL.[18 19] Another audiologic examination was the DPOAE. Two primary frequencies, f1 and f2, were presented simultaneously with f2/f1 equalling 1.22. Twelve points per octave were measured and plotted as a function of f2 ranging about 1.5 kHz to 10 kHz. DPOAE was interpreted to be present if: signal-to-noise ratio (SNR) of DPgrams ≥6 dB at each frequency. In addition, it was normal if the absolute distortion-product (DP) amplitude is in the range of the normative values or above 95th percentile of hearing impaired that based on the Boys Town 65–55 reference set.[20] The deficit of hearing in each frequency is considered if the SNR is less than 6 dB (absent DP response) or the absolute DP amplitude of each frequency is out of the range of the normative values. All participants were tested with hearing assessment tests as described. Subclinical ototoxicity included abnormal hearing response (> 25 dB) or threshold shift of 15 dB or more in HFA (> 8 kHz) and/or abnormal/absent DPOAE. The primary outcome was the presence of a new SNHL, based on conventional audiometry. The secondary outcome was abnormal hearing threshold on HFA or abnormal/absent DPOAE which is called subclinical ototoxicity

Patient and public involvement

Patients and/or the public were not involved in the design, conduct, reporting, or dissemination plans of this research.

Statistical methods

Statistical analyses were performed using SPSS 20.0 for Windows (SPSS Inc., Chicago, IL, USA). Sample size was calculated based on prior literature in 2018 and 2023.[10 12 13] Based on the prevalence of SNHL following early CCS (5.9–6.9%), we used a margin of error of 5% (d=0.05) with a 95% CI (type I error=0.05, two-sided). As a result, the calculated sample size needed was between 85 and 98 participants. Demographics, preoperative, perioperative and postoperative data were presented as frequencies with percentages for the categorical variables and mean±SD or median with IQR for the continuous variables. Comparisons of the hearing thresholds in the pre- and postoperative HFA and DPOAE were analysed, and the prevalence of progressive SNHL and ototoxicity following CCS were calculated. The data for patients with progressive SNHL following CCS detected by the conventional audiometry and patients without progressive SNHL were analysed and compared using χ^2 or the Fisher exact test. Factors associated with SNHL following CCS were analysed using univariate analysis and logistic regression. The factors which represented p value<0.25 in univariate analysis were chosen for binary logistic regression. A p value<0.05 was considered to be statistically significant.

RESULTS

Patient characteristics

A total of 98 paediatric patients who had CHD and underwent CCS in the medical centre were eligible for the analysis (figure 1). The median age was 5.29 years, and 55 (56%) of the included patients were boys. Pre- and postoperative hearing assessments were performed a day prior to surgery and 4.4 (IQR 2.7–8.0) months postoperatively, respectively. Demographic characteristics including clinical features and pre- and postoperative data are shown in table 1. Nine patients (9.2%) had syndromic disorders (4 trisomy 21, 1 velocardiofacial syndrome, 1 Marfan syndrome, 1 Scimitar syndrome, 1 multiple anomalies, 1 foetal alcohol syndrome). Preoperative unilateral hearing impairments were reported in 17 patients (17.3%): nine unilateral SNHL on conventional audiometry, five unilateral abnormal hearing thresholds on HFA and three unilateral conductive hearing loss. These 17 patients were noted to have unilateral HL, and the outcomes were measured from the contralateral ear. The types of lesions are illustrated in figure 2. Most surgical procedures for the patients in the study were in STAT categories 1–3 (88.2%) since most of the procedures were elective and the patients were eligible for the preoperative hearing test (figure 3). Most of the patients (82.7%) used mild hypothermia during CPB. No patients in the study required postoperative ECMO or renal replacement therapy (table 1).

In comparison to their preoperative hearing assessments, 58 patients underwent conventional audiometry plus HFA with DPOAE, and 40 patients underwent ASSR with DPOAE. Notably, four patients (4.1%) showed significantly new abnormal hearing threshold (> 25 dB) or 15 dB shift or more, defined as SNHL on conventional audiometry: three ASSRs and one audiometry (250–8000 Hz). Abnormal DPOAE responses were also noted in all patients. These four patients were classified as SNHL grade 1 WHO classification for hearing loss. Using extended HFA range >8000 Hz, 10 patients (10.2%) were detected newly abnormal hearing response (> 25 dB) or 15 dB shift. Of 10 patients, four patients were additionally shown abnormal DPOAE. There were 33 patients (33.7%) who had postoperative DPOAE abnormalities exclusively (figure 4). Overall, the prevalence of SNHL after CCS in this study was 4.1%. Subclinical hearing impairment which was detected early by extended HFA and DPOAE was 10.2% and 33.6%, respectively, raises the prevalence of subclinical ototoxicity to 43.8%. During the median time of follow-up (20 months), 18 patients with subclinical ototoxicity continued their follow-up at the otology clinic. Among them, two patients exhibited delayed speech, and one patient had an articulation disorder. Notably, one patient with multiple anomalies, including microcephaly, which may lead to global developmental

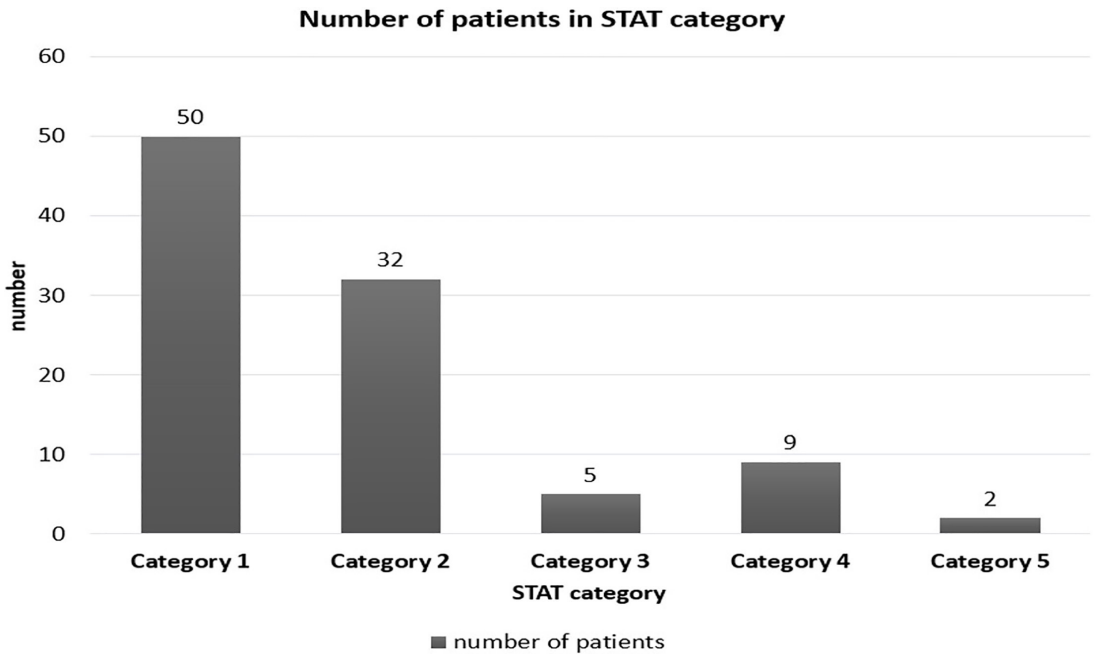

Figure 3 Number of patients in STAT categories 1–5 (n=98). STAT, The Society of Thoracic Surgeons Congenital Heart Surgery.

delay, was identified among these cases. No patients in the study required hearing aids or cochlear implants.

Risks of sensorineural hearing loss (SNHL) following congenital cardiac surgery (CCS)

The risk analysis of SNHL following paediatric CCS is illustrated in table 2. The univariate analysis revealed a significant association between age at surgery younger than 1 year (OR 15.8, 95% CI 1.53 to 162.31, p=0.02) and postoperative SNHL. In the binary logistic regression model, age at surgery younger than 1 year remained independently associated with postoperative SNHL (adjusted OR 18.5, 95% CI 1.2 to 293.8, p=0.04).

DISCUSSION

Herein, we reported a prevalence of postoperative SNHL of 4.1% by using conventional audiometry and subclinical SNHL detected by HFA and DPOAE of 43.8%. High-frequency hearing impairment is mostly affected. The age at surgery younger than 1 year was independently associated with postoperative SNHL (adjusted OR 18.5, 95% CI 1.2 to 293.8, p=0.04). To our knowledge, this is the first study that assessed prevalence of SNHL following CCS in children with pre- and postoperative hearing test using conventional audiometry in addition to HFA and DPOAE to cover subclinical hearing abnormality. An

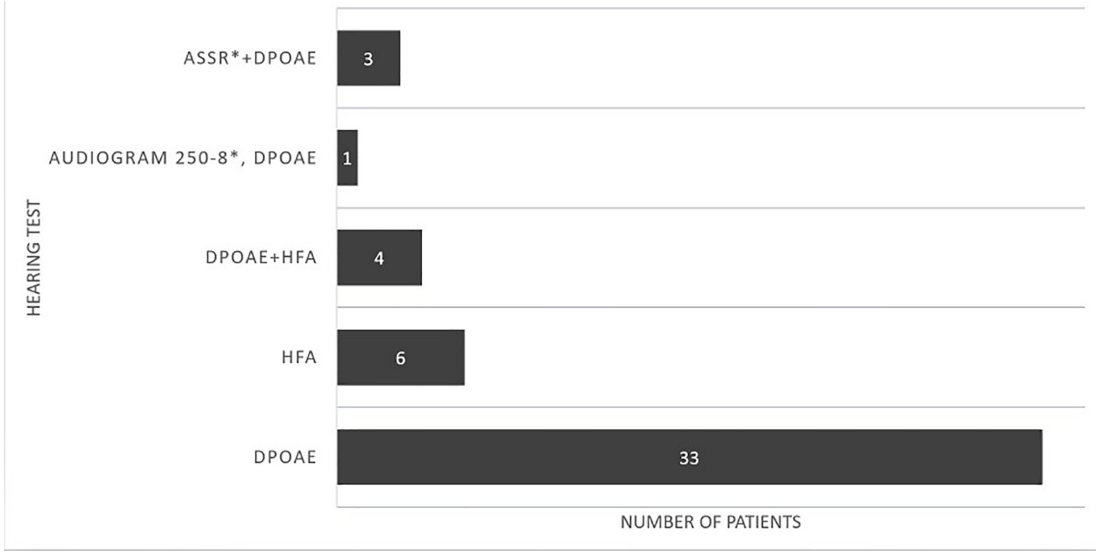

Figure 4 Hearing impairment (n=4) detected by ASSR or conventional audiometry (*) plus DPOAE and subclinical ototoxicity (n=43) detected by DPOAE+HFA or HFA or DPOAE. ASSR, auditory steady-state responses; Audiogram 250–8, conventional audiometry; DPOAE, distortion-product otoacoustic emissions; HFA, extended high-frequency audiometry.

Table 2 Risk factors for SNHL following CCS (n=98)

Variables	Crude OR (95% CI)	P value	Adjusted OR (95% CI)	P value
Male gender	0.7 (0.1, 5.7)	0.801		
Age <1 year at surgery	15.8 (1.5, 162.3)	0.019*	18.5 (1.2, 293.8)	0.038*
Presence of genetic syndromes	3.6 (0.3, 38.6)	0.263		
Single ventricle	0.9 (0.9, 1.0)	0.385		
Cyanotic heart disease	0.9 (0.9, 1.0)	0.293		
Previous cardiovascular surgery	0.9 (0.9, 1.0)	0.569		
Preoperative furosemide	5.3 (0.5, 52.9)	0.149	1.5 (0.1, 24.1)	0.754
Preoperative unilateral SNHL	3.6 (0.3, 38.6)	0.263		
Procedure STAT mortality score >0.6	1.4 (0.2, 10.4)	0.735		
Procedure STAT categories 4–5	0.9 (0.9, 1.0)	0.468		
CPB time >90 min	0.4 (0, 3.6)	0.620		
Moderate hypothermic CPB	1.6 (0.1, 16.6)	0.539		
Postoperative maximal vasoactive inotropic score >20	0.8 (0.1, 8.3)	0.872		
Postoperative usage of dopamine >4 mcg/kg/min	307709498.0 (0, -)	0.997		
Postoperative vancomycin usage	0.9 (0.9, 1.0)	0.674		
Postoperative cumulative furosemide in 72 hours >85 mg	0.9 (0.9, 1.0)	0.220	0 (0, -)	0.998
Postoperative maximal furosemide dosage >4 mg/kg/day	0.8 (0.1, 8.6)	0.897		
Route-intravenous bolus of maximal furosemide	3.9 (0.4, 38.7)	0.217	8.9 (0.7, 118.8)	0.096
Postoperative maximal creatinine level >0.45 (mg/dL)	0.5 (0, 4.7)	0.643		

Adjusted OR by binary logistic regression.
*Statistically significant at p value<0.05.
CCS, congenital cardiac surgery; CPB, cardiopulmonary bypass; SNHL, sensorineural hearing loss; STAT, The Society of Thoracic Surgeons Congenital Heart Surgery.

update systematic review[10] also indicated that the incidence of paediatric hearing loss was 65.6 per 1000 operations which was consistent to our finding. Gopineti *et al*[14] reported that a prevalence of SNHL in children post-repaired or palliated CCS was 11.6% which was higher than our study. It was possibly owing to the preoperative hearing test screening which reduced the confounded cases in our study protocol. Overall, the prevalence of postoperative SNHL is substantially greater than that in the general paediatric population, which has been reported to be 0.2% at birth and 0.35% in adolescence.[21]

Subsequent SNHL following cardiac surgery is related to several possible mechanisms. A few paediatric studies have summarised the risks of SNHL following CCS. El Ganzoury *et al*,[22] for example, found an association between subtle cochlear dysfunction and moderate

hypothermic CPB in paediatric patients having CCS (n=40). In Quebec, a 1–5-year surveillance study of 85 children, post-CCS in infancy, low birth weight and Apgar score at 5 min, and older age at surgery was found to be associated with SNHL.[23] In Gopineti *et al*'s study[14], independent risks were not found from the multivariable analysis. Our findings with the logistic regression analysis showed that age at surgery younger than 1 year (adjusted OR 18.5, 95% CI 1.2 to 293.8, p=0.04) was a significant risk for postoperative SNHL. The plausible explanation may relate with cochlear hypoperfusion after CCS especially in infancy. No associations were found for single ventricle repair, syndromic disorders, moderate hypothermic CBP, furosemide >4 mg/kg/day, or route of administration or duration of intravenous bolus, use of vancomycin, high vasoactive inotropic score, or duration of mechanical ventilation.

While the progression of subclinical ototoxicity and new-onset SNHL after CCS and their impact on neurodevelopmental outcomes are intriguing, they lie beyond the scope of our current research protocol. Initially, our protocol did not include long-term outcome data collection for participants. However, we established follow-up schedules for participants diagnosed with SNHL or subclinical ototoxicity. Over a median follow-up period of 20 months, 18 patients with subclinical ototoxicity continued their follow-up at the otology clinic. Among these cases, two patients exhibited delayed speech, and one had an articulation disorder. Notably, one patient with multiple anomalies, including microcephaly, was identified. This case may involve confounding factors related to developmental delay. Unfortunately, none of the participants diagnosed with SNHL attended their scheduled otology appointments. Future research with more comprehensive data aggregation is necessary to assess the progression and impact of SNHL and subclinical ototoxicity in children following CCS.

STUDY LIMITATIONS

Our prospective study has some limitations since it was conducted during the COVID-19 pandemic. As noted previously, not all survivors following CCS in the medical centre between 2019 and 2023 could be enrolled in the study. Nevertheless, the 98 eligible participants were a sufficiently large group for the analysis based on the prevalence of SNHL in a previous study in 2018 and a systematic review in 2023 that was mentioned in the Methods section.[10 12 13] The eligible participants were selected from all consecutive CCS patients who were clinically stable enough for preoperative hearing assessments. Nonetheless, single ventricle repair and high complexity cases were included in 10–15% of all patients. Regarding hearing method, the ASSR assesses a hearing threshold with maximal frequency of 4000 Hz, not equal to conventional audiometry which is up to 8000 Hz, not extending to 20 000 Hz as HFA. This may indeterminate subclinical ototoxicity in some patients. The variable time interval for postoperative hearing assessments due to COVID-19 pandemic was noted (median 4.4 months, IQR 2.7–8.0 months). This variability allows for the healing process to potentially ameliorate hearing loss or for additional hearing loss from ongoing haemodynamically significant cardiac lesions and cyanosis. Nevertheless, comparing the median time intervals among three groups, postoperative SNHL (n=4), postoperative subclinical hearing loss (n=43) and no postoperative hearing loss (n=51), revealed no statistically significant differences. Lastly, the small sample size of children with SNHL limited the validity of the logistic regression. However, the risk analysis offers a framework for understanding potential associations between risk factors and outcomes, highlighting trends for future studies in this often data-limited field. Thus, table 2 should be interpreted with caution.

CONCLUSION

In this study, the prevalence of new SNHL in the children following CCS is 4.1%. An abnormal hearing threshold from the baseline (based on DPOAE and HFA) is reported for up to 43.8%. High-frequency hearing impairment is mostly affected. Surgery at an age younger than 1 year is associated with a higher incidence of postoperative SNHL. These findings suggest that children undergoing CCS may be at risk for SNHL, potentially increasing risk of neurodevelopmental difficulties. Post-CCS audiological surveillance is recommended for early recognition and timely management particularly in infants under 1 year old.

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