Title

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Journal

Pulmonary Circulation, 14(2)

ISSN

2045-8932

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Publication Date

2024-04-01

DOI

10.1002/pul2.12360

Peer reviewed

DOI: 10.1002/pul2.12360

RESEARCH ARTICLE

Pulmonary Circulation Open Access | PVRI | WILEY

A single institution anesthetic experience with catheterization of pediatric pulmonary hypertension patients

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Funding information
National Institutes of Health, Grant/Award Number: P01 HL146369

Abstract

Cardiac catheterization remains the gold standard for the diagnosis and management of pediatric pulmonary hypertension (PH). There is lack of consensus regarding optimal anesthetic and airway regimen. This retrospective study describes the anesthetic/airway experience of our single center cohort of pediatric PH patients undergoing catheterization, in which obtaining hemodynamic data during spontaneous breathing is preferential. A total of 448 catheterizations were performed in 232 patients. Of the 379 cases that began with a natural airway, 274 (72%) completed the procedure without an invasive airway, 90 (24%) received a planned invasive airway, and 15 (4%) required an unplanned invasive airway. Median age was 3.4 years (interquartile range [IQR] 0.7–9.7); the majority were either Nice Classification Group 1 (48%) or Group 3 (42%). Vasoactive medications and cardiopulmonary resuscitation were required in 14 (3.7%) and eight (2.1%) cases, respectively; there was one death. Characteristics associated with use of an invasive airway included age <1 year, Group 3, congenital heart disease, trisomy 21, prematurity, bronchopulmonary dysplasia, WHO functional class III/IV, no PH therapy at time of case, preoperative respiratory support, and having had an intervention ($p < 0.05$). A composite predictor of age <1 year, Group 3, prematurity, and any preoperative respiratory support was significantly associated with unplanned airway escalation (26.7% vs. 6.9%, odds ratio: 4.9, confidence interval: 1.4–17.0). This approach appears safe, with serious adverse event rates similar to previous reports despite the predominant use of natural airways. However, research is needed to further investigate the optimal anesthetic regimen and respiratory support for pediatric PH patients undergoing cardiac catheterization.

KEYWORDS
airway, anesthesia, pediatric pulmonary vascular disease, sedation

INTRODUCTION

Despite significant advances in the field, pulmonary vascular disease remains a major source of morbidity and mortality for neonates, children, and adolescents globally.[1–5] Noninvasive imaging modalities, such as advanced echocardiography and magnetic resonance imaging, have important roles in screening, diagnosis, and disease monitoring.[1,2] However, invasive cardiac catheterization remains the "gold standard" for the diagnosis and management of pediatric pulmonary vascular disease. In addition to obtaining direct pressure measurements, catheterization facilitates the determination of cardiac output, vascular resistances, vascular reactivity, and the ability to perform interventional procedures.[1,6–15]

Despite these advantages, the need for anesthesia or sedation adds an additional layer of complexity to the choice to proceed with cardiac catheterization in pediatric patients.[6–9] The reported risk of serious adverse events during cardiac catheterization for pediatric pulmonary hypertension (PH) patients is variable, ranging from 2% to 6%.[6–11,15–23] Identified risk factors during cardiac catheterization include younger age, longer duration of procedure, suprasystemic pulmonary arterial pressures, right ventricular dysfunction, advanced functional class (III/IV), and treatment naiveté.[6–11,15–21,23] However, the type of anesthesia or respiratory support utilized has not been clearly identified as a risk factor.[11,17,19–25]

Thus, there is a lack of consensus regarding the optimal anesthetic regimen and respiratory support for pediatric pulmonary vascular disease cardiac catheterization.[25] Broadly speaking, the two approaches are sedation with a natural (noninvasive) airway and general anesthesia with an artificial (invasive) airway. The advantages of a natural airway approach include obtaining reliable hemodynamics during spontaneous breathing, thereby mitigating the effects of positive pressure ventilation on cardiac output, pulmonary and systemic hemodynamics, and potentially mitigating the hemodynamic perturbations surrounding induction of anesthesia and airway management.[11,16,17,26–29] The advantages of an invasive airway include the facilitated ability to maintain normal oxygenation, ventilation, and pH, important modulators of pulmonary vascular resistance, and having a controlled airway in the event of acute hemodynamic compromise or collapse.[30]

We believe that obtaining accurate reliable hemodynamic data that correlates most closely with the patient's normal state is of utmost importance, and that there is no evidence that an invasive airway decreases adverse events. Thus, the consensus of our program is to preferentially use a combination of intravenous anesthetic agents to support a natural airway with spontaneous breathing. The objectives of this retrospective study were to[1] describe our cohort of pediatric PH patients undergoing cardiac catheterization;[2] describe our anesthetic approach of preferentially utilizing natural airways;[3] describe the characteristics of those who received noninvasive versus invasive airway support; and [4] investigate potential predictors of patients requiring unplanned escalation of airway support during cardiac catheterization.

METHODS

Study design

This is a retrospective cohort study of infants and children with a diagnosis of PH who underwent cardiac catheterization at UCSF Benioff Children's Hospital between January 1, 2015, and December 1, 2021. Eligible subjects were identified via an internal database maintained by our institution's pediatric PH consult service. Exclusion criteria included age >21 years and presence of an in situ invasive airway with associated mechanical ventilation at time of catheterization. The University of California San Francisco's Institutional Review Board approved the study protocol.

Data collection

Data were obtained by retrospective medical record review. Patient-specific demographic and clinical characteristics as well as preoperative, intraoperative, and postoperative characteristics related to each individual cardiac catheterization and anesthesia encounter were collected. Airway type was defined as invasive (endotracheal tube, laryngeal

TABLE 1 Demographic and clinical characteristics of pediatric pulmonary hypertension patients undergoing cardiac catheterization ($n = 232$ patients).

Demographic characteristics	*N* (%), median (interquartile range [IQR], range)
Female sex	121 (52.2)
Race	
Caucasian	76 (32.8)
Hispanic	52 (22.4)
African American	22 (9.5)
Asian	45 (19.5)
Other	37 (15.9)
Status at time of data collection	
Alive	196 (84.5)
Deceased	35 (15.1)
Lost to follow-up	1 (0.4)
Clinical characteristics	
PH Classification (by Nice classification[32])	
Pulmonary arterial hypertension (Group 1)	*112 (48.3)*
Idiopathic/Hereditary	20 (8.6)
Acquired - congenital heart disease	86 (37.1)
Other acquired	6 (2.6)
Left heart disease (Group 2)	*10 (4.3)*
Respiratory disorders (Group 3)	*98 (42.2)*
Congenital diaphragmatic hernia	66 (28.5)
Bronchopulmonary dysplasia	20 (8.6)
Other lung disease	12 (5.2)
Other	*12 (5.2)*
Congenital heart disease present	*176 (75.9)*
ASD	18 (7.8)
VSD	13 (5.6)
PDA	31 (13.4)
Combined (ASD ± VSD ± PDA)	31 (13.4)
Complete atrioventricular canal defect	11 (4.7)
Left-sided obstructive disease	21 (9.1)
Pulmonary vein stenosis	16 (6.9)
Transposition of the great vessels	6 (2.6)
Other	29 (12.5)
History of prematurity (<37 weeks gestational age)	102 (44.0)
Trisomy 21	28 (12.1)
Other genetic syndrome	38 (16.4)
History of bronchopulmonary dysplasia	76 (32.8)
Number of catheterizations over study period	2 (IQR 1–3, range 2–11)

Abbreviations: ASD, atrial septal defect; PDA, patent ductus arteriosus; VSD, ventricular septal defect.

mask airway, tracheostomy with ventilator support) or noninvasive (nasal cannula, high-flow nasal cannula (HFNC), bilevel positive airway pressure (BiPAP), continuous positive airway pressure (CPAP), bag mask, nonrebreather, tracheostomy without ventilator support). Extensive review of anesthesia records and notes was performed for the subset of patients who required an invasive airway to further define whether the invasive airway was part of the original anesthesia plan. All data were entered into Research Electronic Data Capture (REDCap), a secure password-protected database.[31] Each patient was assigned a unique study number.

Statistical analysis

Comparisons between distributions of categorical variables were performed by chi-square tests. Continuous normally distributed variables were presented as mean and standard deviation and compared by *t*-tests. Non-normally distributed continuous data were presented in median and interquartile range (IQR) and compared with Wilcoxon rank-sum tests. Univariate logistic regression models were used to analyze variables associated with the presence of an invasive airway. When hemodynamic data were dichotomized for analysis, the median value was used. Nonindependence for multiple catheterizations of the same patients was accounted for by clustering by unique patient study number. Results were presented in odds ratios (OR) and 95% confidence intervals (CI). $p < 0.05$ was considered statistically significant. Data analysis was performed using Stata (version 15, StataCorp).

RESULTS

Between January 1, 2015, and December 1, 2021, a total of 448 cardiac catheterizations were performed in 232 neonates, children, and adolescents with known and/or suspected PH. Of the 448 cases, 379 (84.6%) entered the catheterization laboratory without an invasive airway in situ and formed the primary cohort for analysis. The 69 cases that already had an invasive airway with associated mechanical ventilation were excluded (Tables S1A,B).

Demographic and clinical characteristics of the 232 patients are described in Table 1. Patients were categorized by Nice classification as Group 1 (48.3%), Group 2 (4.3%), Group 3 (42.2%), and other (5.2%) (Figure 1).[32] Female sex comprised 52% of the cohort; 75.9% had congenital heart disease, 44% had a history of prematurity (<37 weeks gestational age), 32.8% had a history of bronchopulmonary dysplasia, and 28.5% had a genetic syndrome (Trisomy 21 in 12.1%).

Preoperative characteristics pertaining to each patient at time of catheterization are shown in Table 2. Median age at time of catheterization was 3.4 years (IQR: 0.7–9.7, range 0–21). Greater than 30% of the cohort were <1 year of age, 31.3% were WHO functional class III/IV, and 58.6% required some baseline respiratory support. Almost two-thirds of cases (74.1%) had a preprocedural estimated RV pressure by cardiac echocardiography of >50% of systemic values. Indications for cardiac catheterization included evaluation of the response to therapy (52.8%) and initial diagnostic evaluation (20.3%). Approximately one-third (33.5%) of cases were performed in patients who were not on PH medications and 24.5% were being treated with triple therapy, which included a phosphodiesterase (PDE) inhibitor, an endothelin receptor antagonist (ERA), and a prostacyclin. Interestingly, within the group that was undergoing initial diagnostic evaluation, 58 (75.3%) were on no therapy at the time of catheterization, 13 (16.9%) were on inhaled nitric oxide (iNO) alone, three (3.9%) were on a PDE inhibitor alone, and three (3.9%) were on an ERA alone.

The anesthetic approach included a premedication in 50.1% of cases ($n = 190$). Standard American Society of Anesthesiology (ASA) monitoring was used including noninvasive blood pressure, five lead EKG, pulse oximeter, and $EtCO_2$ though a sampling line of the nasal cannula or other interface. After preoperative assessment, depending on the patient airway anatomy, risk factors, and cardiac catheterization needs, the anesthesiology team in consultation with interventional cardiology team decided on the type of airway best suitable for the safe conduct of the procedure. Inhalational induction was used to facilitate venous access in 50.9% patients ($n = 193$). Intraoperative anesthetic agents included dexmedetomidine (91.0%, $n = 345$), midazolam (62.8%, $n = 238$), ketamine (62.8%, $n = 238$), propofol (38.0%, $n = 144$), fentanyl (27.7%, $n = 105$), and inhaled gases (63.3%, $n = 240$, including those who had an inhalational induction).

Baseline hemodynamics demonstrated a mean pulmonary arterial pressure of 33.5 mmHg (IQR: 23–44, range 8–92) and a PVRi of 5.2 Woods Units (IQR: 3.3–8, range 1–52.3) (Table 3). The highest level of respiratory support during the procedure was oxygen delivered via nasal cannula in 238 (62.8%); high flow nasal cannula in 21 (5.5%); laryngeal mask airway in 22 (5.8%), and endotracheal tube in 80 (21.4%) (Table 3, Figure 2). Of the cases that started with a tracheostomy without ventilator support ($n = 10$), three were placed on ventilator support during the procedure. Postprocedural respiratory support included none (51; 11.4%), oxygen delivered via nasal cannula (222; 58.6%), oxygen delivered via high flow nasal cannula or BiPAP/CPAP (37; 9.8%), (222; 58.6%), and an endotracheal tube (59; 15.6%). Vasoactive medications were initiated in 14 (3.7%), and a total of 62 (16.4%) underwent catheter-based interventions. Cardiopulmonary resuscitation (CPR) was

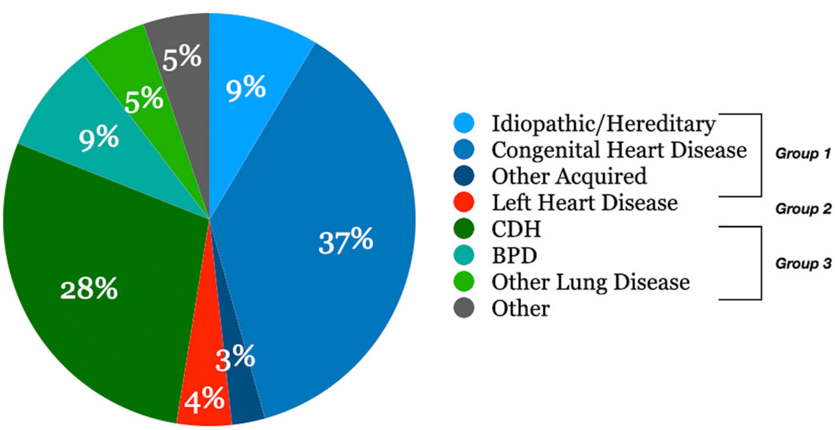

FIGURE 1 Nice classification of pulmonary hypertension in study cohort ($n = 232$ patients).

TABLE 2 Preoperative assessment of pediatric pulmonary hypertension patients undergoing cardiac catheterization ($n = 379$).

Preoperative characteristics	*N* (%) or median (interquartile range [IQR], range)
Age at time of catheterization	
<1 month	3 (0.8)
1 month–1 year	111 (29.3)
1–3 years	66 (17.4)
3–12 years	125 (33.0)
>12 years	74 (19.5)
Preoperative location	
Cardiac intensive care unit	97 (25.6)
Pediatric Intensive care unit	41 (10.8)
Intensive care nursery	63 (16.6)
Home	157 (41.4)
Other	21 (5.5)
WHO functional classification ($n = 358$)	
I	76 (21.2)
II	170 (47.5)
III	81 (22.6)
IV	31 (8.7)
Pediatric functional class at catheterization ($n = 355$)	
I	57 (15.0)
II	139 (36.7)
IIIa	81 (21.4)
IIIb	45 (11.9)
IV	33 (8.7)
American Society of Anesthesiology class ($n = 377$)	
I	0
II	2 (0.5)
III	120 (31.8)
IV	248 (65.8)
V	7 (1.9)
Baseline oxygen or respiratory support	
None	156 (41.2)
Nasal cannula (day and night)	94 (24.8)
Nasal cannula (night only)	51 (13.5)
High-flow nasal cannula (HFNC)	13 (3.5)
Bilevel positive airway pressure (BiPAP)/continuous positive airway pressure (CPAP)	45 (11.9)
BiPAP/CPAP (night only)	10 (2.6)
Tracheostomy—not ventilator dependent	10 (2.6)
PH therapies	
None	127 (33.5)
Nitric oxide alone	14 (3.7)
PDE5 inhibitor only	53 (14.0)
Endothelin receptor antagonist (ERA) only	19 (5.0)
Prostacyclin only	3 (0.8)
PDE5 inhibitor and ERA	53 (14.0)
PDE5 inhibitor and prostacyclin	11 (2.9)
ERA and prostacyclin	6 (1.6)
PDE5 inhibitor + ERA + prostacyclin	93 (24.5)
Estimated RV pressure by echocardiogram[a] ($n = 321$)	
<50% systemic	83 (25.9)
≥50% systemic	148 (46.1)
At least systemic	90 (28.0)
Indication for Catheterization	
Initial diagnostic evaluation	77 (20.3)
Evaluation of response to therapy	200 (52.8)
Intervention	33 (8.7)
Clinical decompensation	18 (4.7)
Multiple/other	51 (13.5)

[a]Echocardiogram obtained within 1 week of catheterization.

required in eight (2.1%) procedures. Of those who required CPR, four had planned invasive airways, three had unplanned invasive airways, and one remained with a noninvasive airway. There was one death (0.3%). This patient had a repaired severe congenital diaphragmatic hernia, lung hypoplasia, and repaired atrioventricular septal defect with residual valvular regurgitation. She was chronically on Noninvasive continuous positive airway pressure and had a planned invasive airway for the procedure. She suffered a cardiac arrest upon induction/intubation, was successfully resuscitated, but had progressive hypoxemia and hypercarbia unresponsive to therapy.

Of the 379 cases that began with a natural airway, 274 (72.3%) completed the procedure without an invasive

TABLE 3 Intraoperative and postoperative characteristics of pediatric pulmonary hypertension patients undergoing cardiac catheterization ($n = 379$).

Intraoperative characteristics	*N* (%) or median (interquartile range [IQR], range)
Respiratory support	
Highest level of respiratory support	
Nasal cannula	238 (62.8)
High-flow nasal cannula (HFNC) or bilevel positive airway pressure (BiPAP)/continuous positive airway pressure (CPAP)	21 (5.5)
Endotracheal tube	80 (21.4)
Laryngeal mask airway	22 (5.8)
Tracheostomy—ventilator support	3 (0.8)
Tracheostomy—no ventilator support	7 (1.8)
Bag mask or nonrebreather	8 (2.1)
Nitric oxide use	
Vasoreactivity testing only	180 (61.4)
Clinically indicated	30 (7.9)
Procedural course	
Baseline condition hemodynamics	
mRAP (mmHg)[2]	7 (IQR 5–8, range 1–23)
mPAP (mmHg)	33.5 (IQR 23–44, range 8–92)
mPAP/mean arterial pressure ratio	0.54 (IQR 0.37–0.77, range 0.10–2.0)
mLAP or PCWP (mmHg)[3]	10 (IQR 8–13, range 3–59)
CI (L/min/m^2)[4]	3.3 (IQR 2.8–3.9, range 1.5–24.6)
PVRi (woods units)[5]	5.2 (IQR 3.3–8, range 1–52.3)
PCO_2 on arterial blood gas ($n = 239$)	46 (IQR 41–52)
PO2 on arterial blood gas ($n = 239$)	71 (IQR 58–86)
Cardiopulmonary resuscitation required	8 (2.1)
Death	1 (0.26)
Vasoactive medication initiated	14 (3.7)
Catheter-based intervention performed	62 (16.4)
Postoperative characteristics	N (%) or median (IQR, range)
Postoperative airway	
No support or blow-by oxygen	51 (11.4)
Nasal cannula	222 (58.6)
HFNC or BiPAP/CPAP	37 (9.8)
Endotracheal tube	59 (15.6)
Tracheostomy—ventilator support	2 (0.5)
Tracheostomy—no ventilator support	8 (2.1)
Postoperative disposition	
Intensive care unit	286 (75.4)
PACU/Home	83 (21.9)
Deceased	1 (0.3)
Other	9 (2.4)

Abbreviation: PACU, post anesthesia care unit.

airway (Figure 3). Of the 105 encounters that received an invasive airway, 90 (23.7% of the entire $n = 379$ cohort) were planned at the outset of the procedure. Fifteen of the encounters had an unplanned escalation to an invasive airway (3.9%). Reasons for unplanned escalation included respiratory failure ($n = 12$) and hemodynamic compromise ($n = 3$).

Characteristics associated with cases that received an invasive airway versus continued with a Noninvasive airway are described in Table 4. Characteristics included age <1 year, PH Nice Group 3 classification, presence of congenital heart disease, trisomy 21, a history of prematurity and bronchopulmonary dysplasia, functional class III/IV, no PH therapy at the time of the case, preoperative ICU location, having an intervention performed, and any preoperative respiratory support ($p < 0.05$, Table 4). Patients receiving preprocedural triple PH therapy had a lower incidence of having received an invasive airway (12.4% vs. 29.2%, $p = 0.005$) (Table 4). Characteristics associated with the need for unplanned escalation to an invasive airway included age <1 year and a history of prematurity (Table 5). A composite predictor including age <1 year, PH Group 3, history of prematurity, and any baseline respiratory support was also significantly associated with unplanned airway escalation (26.7% vs. 6.9%, OR: 4.9, CI: 1.4–17.0) (Table 5).

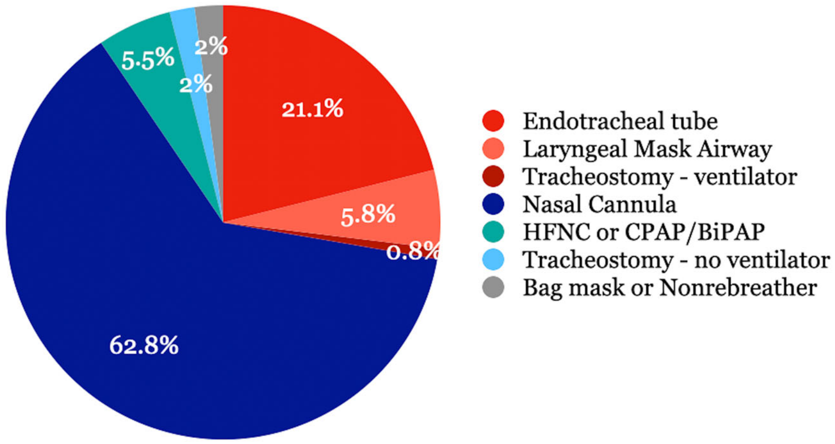

FIGURE 2 Highest level of respiratory support during catheterization of pediatric pulmonary hypertension cohort ($n = 379$ cases).

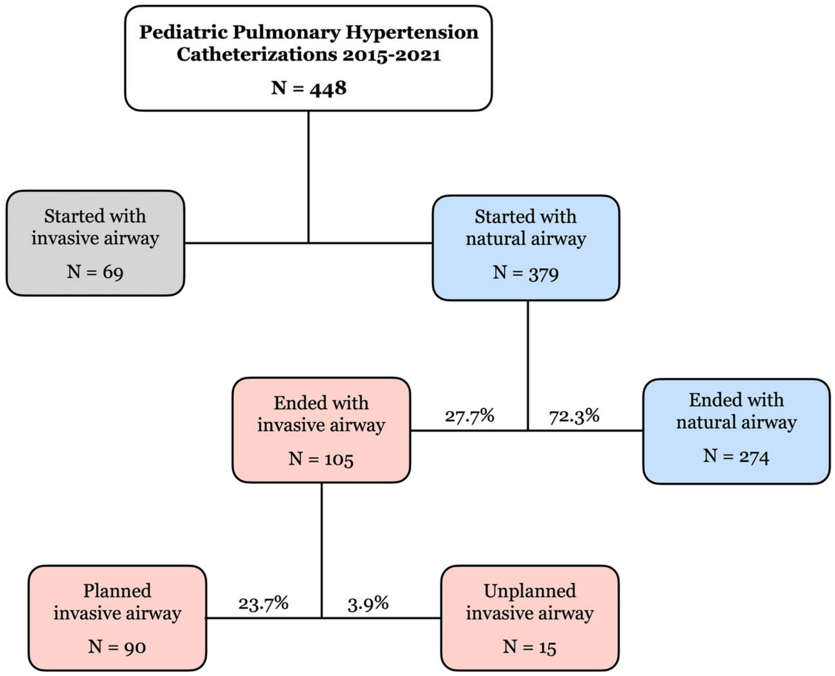

FIGURE 3 Airway type during pediatric pulmonary hypertension catheterization ($n = 379$ cases). Invasive airway is defined as endotracheal tube, laryngeal mask airway, or tracheostomy with ventilator support. Natural airway is defined as those receiving nasal cannula, high-flow nasal cannula, bilevel positive airway pressure, continuous positive airway pressure, bag mask, non-rebreather, or tracheostomy without ventilator support.

DISCUSSION

In this retrospective case series, we describe the anesthetic experience of our single center cohort of pediatric PH patients undergoing cardiac catheterization. Similar to other PH cardiac catheterization cohorts and pediatric PH epidemiology studies, the majority of our patients were either Nice classification Group 1 (48.3%) or 3 (42.2%), with a large subset that were infants (30.1%), had a history of prematurity (44%), bronchopulmonary dysplasia (32.8%), congenital heart disease (75.9%), and genetic syndromes (28.4%) (Tables 1 and 2).[3,4,6,11,15,33–35] Given our institutional bias to optimally obtain hemodynamic assessments during spontaneous breathing, our anesthetic approach is to proceed with a noninvasive airway whenever deemed safe. Hence, despite epidemiologic similarities, the use of a noninvasive airway in our cohort (72.2%) was significantly higher than previous reports ranging between ~1% and 55%.[8,11,15,17,24,25] In addition, Lin et al reported that six of eight large PH centers prefer use of invasive airways over noninvasive airways for cardiac catheterization.[25]

Our preference toward obtaining hemodynamic data on spontaneous breathing patients is based upon the well-described effects of positive pressure ventilation and anesthesia on pulmonary and systemic vascular resistance and cardiac hemodynamics, as well as on cardiopulmonary interactions. In the resting state, intrapleural pressure (i.e., intrathoracic pressure) is slightly negative. With the onset of spontaneous respiration, the contraction of the diaphragm and intercostal muscles produce a further decrease in pleural pressure. This results in an increase in venous return, a decrease in pulmonary vascular resistance, and an increase in systemic vascular

TABLE 4 Characteristics associated with pediatric pulmonary hypertension patients with an invasive versus noninvasive airway during cardiac catheterization ($n = 379$).

Characteristic	Noninvasive Airway ($n = 274$)	Invasive airway ($n = 105$)	Crude odds ratio	95% confidence interval	*p*-Value
Age <1 year	58 (21.2%)	56 (53.3%)	4.3	2.5–7.3	<0.001
Female	168 (61.5%)	55 (52.4%)	0.7	0.4–1.2	0.165
PH nice classification					
Group 1	177 (64.6%)	48 (45.7%)	Ref		
Group 3	69 (25.2%)	47 (44.8%)	2.5	1.4–4.2	0.001
All other	28 (10.2%)	10 (9.5%)	1.3	0.5–3.2	0.587
Congenital heart disease present	200 (73.0%)	88 (83.8%)	1.9	1.04–3.6	0.038
Trisomy 21	28 (10.5%)	21 (20.2%)	2.1	1.1–4.3	0.026
Other genetic syndrome	47 (17.2%)	16 (15.2%)	0.9	0.4–1.8	0.694
History of prematurity (<37 weeks)	72 (27.7%)	41 (39.8%)	1.7	1.02–2.9	0.04
History of BPD	43 (17.0%)	32 (32.3%)	2.3	1.3–4.2	0.005
Pediatric Functional Class III/IV	95 (34.7%)	64 (60.9%)	2.9	1.8–4.7	<0.001
Triple PH therapy	80 (29.2%)	13 (12.4%)	0.3	0.2–0.7	0.005
No PH therapy	81 (29.7%)	46 (43.4%)	1.8	1.2–2.9	0.009
RV pressure estimate at least systemic by echocardiogram	61 (22.3%)	29 (27.6%)	1.3	0.7–2.4	0.336
Preoperative location ICU	128 (46.7%)	73 (69.5%)	2.6	1.6–4.2	<0.001
Intervention performed	35 (13.0%)	27 (25.7%)	2.3	1.3–4.1	0.004
PDA closure	13 (4.7%)	13 (12.4%)	2.8	1.1–7.0	0.024
ASD closure	8 (2.9%)	1 (0.9%)	0.3	0.04–2.6	0.286
Pulmonary vein intervention	2 (0.7%)	6 (5.7%)	8.2	2.5–26.7	<0.001
Other intervention	12 (4.4%)	7 (6.7%)	1.6	0.6–3.9	0.341
PVRi >5.2 WU	137 (50.0%)	49 (46.7%)	0.9	0.6–1.4	0.561
Mean PA pressure >34 mmHg	130 (48.3%)	50 (47.6%)	0.9	0.6–1.6	0.972
ASA class ≥4	178 (65.0%)	77 (73.3%)	1.5	0.9–2.5	0.150
Any preoperative respiratory support	140 (51.1%)	82 (78.1%)	3.4	1.9–6.1	<0.001

Note: Results displayed as *n* (%) or odds ratio with 95% confidence interval. All analyses clustered by patient.
Abbreviations: ASA, American Society of Anesthesiologists; ASD, atrial septal defect; BPD, bronchopulmonary dysplasia; ICU, intensive care unit; PA, pulmonary artery; PDA, patent ductus arteriosus; PH, pulmonary hypertension; PVRi, pulmonary vascular resistance index; RV, right ventricle.

resistance. Conversely, positive pressure ventilation increases transpulmonary pressure resulting in compression of pulmonary vascular capillaries and an increase in pulmonary vascular resistance. In addition, pleural pressure is increased, which decreases venous return and decreases systemic vascular resistance secondary to an increase in aortic pressure and subsequent baroreceptor activation.[9,28,29] Furthermore, increases in positive end-expiratory pressure may accentuate the decrease in venous return and decline in cardiac output.[26–29] Thus, we believe that obtaining hemodynamic data during spontaneous respiration with a noninvasive airway more accurately reflects a patient's baseline hemodynamic state.[9,36] Given the effect of hypercarbic acidosis on pulmonary vascular hemodynamics, it is important to note that adequate ventilation was maintained in our noninvasive airway cohort, as reflected by a normal pCO_2 on arterial blood gas analysis (Table 3).[30] Lastly, two of the most frequently used anesthetics in our cohort were dexmedetomidine and ketamine, both with minimal effects on pulmonary vascular hemodynamics, further

TABLE 5 Characteristics associated with requirement for unanticipated airway escalation in pediatric pulmonary hypertension patients undergoing cardiac catheterization ($n = 289$).

Characteristic	Noninvasive airway ($n = 274$)	Unplanned invasive airway ($n = 15$)	Crude odds ratio	95% confidence interval	*p*-Value
Age <1 year	58 (21.2%)	7 (46.7%)	3.3	1.1–9.6	0.033
Female	168 (61.3%)	7 (46.7%)	0.6	0.2–1.6	0.263
PH nice classification					
Group 1 PH	177 (64.6%)	8 (53.3%)	Ref		
Group 3 PH	69 (25.2%)	6 (40.0%)	1.9	0.6–5.7	0.239
All other	28 (10.2%)	1 (6.7%)	0.8	0.1–6.8	0.831
Congenital heart disease	200 (73.0%)	13 (86.7%)	2.4	0.5–10.9	0.256
Trisomy 21	28 (10.5%)	2 (13.3%)	1.3	0.3–6.7	0.739
Other genetic syndrome	47 (17.2%)	6 (30.0%)	2.1	0.7–6.0	0.186
Prematurity (<37 weeks)	72 (26.3%)	8 (53.3%)	3.2	1.1–9.1	0.029
History of BPD	43 (15.7%)	5 (33.3%)	2.7	0.9–8.0	0.08
Pediatric functional class III/IV	95 (34.7%)	6 (40.0%)	1.3	0.4–3.7	0.129
Triple PH therapy	80 (29.2%)	4 (26.7%)	0.9	0.3–2.8	0.829
Any PH therapy versus none	193 (70.4%)	8 (53.3%)	0.5	0.2–1.4	0.165
RV pressure estimate at least systemic by echocardiogram	61 (22.3%)	2 (13.3%)	0.5	0.1–2.3	0.404
Preoperative location ICU	128 (46.7%)	7 (46.7%)	1.0	0.3–2.8	0.997
Intervention performed	35 (13.0%)	2 (13.3%)	1.0	0.2–4.9	0.968
PVRi >5.2 WU	137 (50.0%)	5 (33.3%)	0.5	0.2–1.5	0.208
Mean PA pressure >34 mmHg	130 (48.3%)	5 (33.3%)	0.5	0.2–1.6	0.259
ASA Class ≥ 4	178 (65.0%)	8 (53.3%)	0.6	0.2–1.8	0.371
Any preoperative respiratory support	140 (51.1%)	10 (66.7%)	1.9	0.6–6.0	0.264
Composite predictor: age <1 year and prematurity and group 3 PH, and any preoperative respiratory support	19 (6.9%)	4 (26.7%)	4.9	1.4–17.0	0.013

Note: Results displayed as *n* (%) or odds ratio with 95% confidence interval.

Abbreviations: ASA, American Society of Anesthesiologists; BPD, bronchopulmonary dysplasia; ICU, intensive care unit; PA, pulmonary artery; PH, pulmonary hypertension; PVRi, pulmonary vascular resistance index; RV, right ventricle.

emphasizing the focus on obtaining data in as close to a normal baseline state as possible.[37–39]

Safety issues related to the use of invasive airways include hypoxemia and hemodynamic compromise during induction with endotracheal intubation.[17,40] For example, acute pulmonary hypertensive episodes have been reported with induction and endotracheal intubation.[15,19,41,42] Conversely, the lack of having a controlled airway in the setting of acute decompensation is a potential important safety issue related to using a noninvasive airway. In some reports, anesthesia with the use of invasive airways has been shown to be a risk factor for adverse events.[11,23,25] However, this has not been a consistent finding, with other reports demonstrating no differences in adverse outcomes associated with airway management.[17,24,43] Given the small sample size, diverse patient populations, and retrospective nature of these reports that are vulnerable to patient selection bias, it is difficult to determine the isolated effect of airway choice on outcomes. Importantly, the incidence of adverse outcomes (CPR and death) in our cohort was similar to previous reports despite the predominant use of noninvasive airways.[6–11,15,20–23,36]

Characteristics associated with having had an invasive (planned and unplanned) versus noninvasive airway included age <1 year, Group 3 PH Nice Classification, history of prematurity, congenital heart disease, trisomy 21, functional class III/IV, no PH therapy at the time of the case, preoperative ICU location, preoperative respiratory support, and having had an intervention performed (Table 4). Most of these factors likely reflect that patients with greater overall illness severity were more likely to have had an invasive airway as part of their preoperative anesthesia plan. Trisomy 21 is not surprising given its association with airway obstruction. PH therapy-naïve patients were also more likely to have had an invasive airway, likely reflecting greater preoperative concern about severity of disease and risk for cardiopulmonary decompensation. Moreover, securement of the airway is typical when the catheterization plan involves an intervention.

Fifteen (3.9%) of the encounters had an unplanned escalation to an invasive airway (Figure 3), which is consistent with rates of airway conversion found in similar studies. In a retrospective study of children <2 years old undergoing cardiac catheterization, Mikus and colleagues demonstrated a 4% conversion rate to an invasive airway in the 54% of the cohort that began with a noninvasive airway.[24] Similarly, utilizing a large multi-institutional collaborative database, Lin and colleagues demonstrate that in the 31% of procedures performed with a noninvasive airway, 1.8% converted to an invasive airway.[25] In this cohort, age <1 year and continuous vasoactive support were independently associated with the need to convert to an invasive airway. In the current report, in univariable analysis, we also identified age <1 year as a risk factor for airway conversion, in addition to a history of prematurity. However, it is noteworthy that 21.2% of our cohort that started and completed the procedure with a noninvasive airway were <1 year of age (Table 4). A composite predictor of age <1 year, PH Group 3, history of prematurity, and any baseline respiratory support was significantly associated with the need for unplanned escalation of airway support in our cohort (OR: 4.9) (Table 5).

In summary, we report our institutional practice of utilizing a noninvasive airway for pediatric PH catheterizations when deemed safe, to obtain hemodynamic data during a spontaneous breathing condition. In fact, the maintenance of a noninvasive airway in >70% of procedures represents one of the highest rates reported to date.[8,11,15,17,24,25] This is despite a high-risk cohort with ~one-third age under 1 year and greater than 50% requiring some baseline respiratory support. In addition, we identify characteristics associated with the need for conversion to an invasive airway, which may guide airway management. In general, this approach appears safe, with serious adverse event rates similar to previous reports.[6–11,15,20–23,36] However, limitations of this report are noteworthy, particularly its retrospective nature and small sample size. Thus, conclusions regarding differences in hemodynamics and outcomes associated with the choice of an invasive versus noninvasive airway cannot be made or insinuated. Most importantly, a careful, thoughtful overall anesthetic approach with an experienced pediatric cardiac anesthesiology and PH collaborative team, that includes specialized areas for pre- and postprocedural monitoring, is vital to reducing adverse events and optimizing data acquisition.[6–11,15–17,20–25,36,43,44]

AUTHOR CONTRIBUTIONS

Each author has participated sufficiently in the work including substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data, and has drafted or revised this manuscript critically for important intellectual content and final approval of the version to be submitted and published. Each author takes full responsibility for the integrity of the work as a whole, from inception to published article.

ACKNOWLEDGMENTS

This study was funded by NIH P01 HL146369 (Jeffrey R. Fineman).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

ETHICS STATEMENT

IRB approval obtained from the University of California San Francisco IRB Committee.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Morell E, Colglazier E, Becerra J, Stevens L, Steurer MA, Sharma A, Nguyen H, Kathiriya IS, Weston S, Teitel D, Keller R, Amin EK, Nawaytou H, Fineman JR. A single institution anesthetic experience with catheterization of pediatric pulmonary hypertension patients. Pulm Circ. 2024;14:e12360. https://doi.org/10.1002/pul2.12360