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Improving efficiency of cardiac magnetic resonance imaging for children with pulmonary hypertension

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ABSTRACT:

Background: Right ventricular (RV) failure is an important cause of morbidity and mortality in pulmonary hypertension (PH). However, access to pediatric CMR – the gold standard for RV assessment – can be limited by sedation needs, tolerance of prolonged exams, and intravenous access for contrast. We hypothesize that a focused PH-specific CMR protocol could address these limitations and standardize image acquisition at our institution.

Methods: We performed a retrospective (1/2018-12/2025) single-center study of pediatric PH patients referred for CMR. Patient and CMR characteristics were collected via chart review. A PH CMR protocol was implemented in late 2022 with additional clinician education in 1/2024. Outcomes were compared across three eras: pre-protocol implementation (era 1), post-protocol implementation (era 2), and after additional clinical education (era 3).

Results: We identified 129 CMR examinations in 57 PH patients (era 1: ~10 exams/year, era 2: 28 exams/year, era 3: ~26 exams/year). Despite increasing patient complexity and center volume, exam duration decreased after protocol implementation (era 1: 40 minutes [IQR 33-50] vs. era 3: 32 minutes [IQR 27-36], p=0.003), reflecting shortened first-time CMR duration and decreased number of extraneous sequences. Contrast administration decreased (era 1: 26/48 [54.2%] vs. era 3:16/53 [30.2%], p=0.007) but anesthesia use remained consistent across eras.

Conclusions: A focused PH CMR protocol was associated with shorter exam duration, improved image acquisition standardization, and reduced contrast administration despite increasing patient complexity and center volume. These findings support indication-specific CMR protocols in pediatric PH. Follow-up is needed to determine whether focused protocols reduce anesthesia use in younger children.

INTRODUCTION

Pulmonary hypertension (PH) is characterized by elevated pulmonary artery pressures in the setting of diverse and progressive pulmonary vascular pathology [1–4]. Right ventricular (RV) failure is the leading cause of death in PH [1,3], making the non-invasive RV assessment central to prognosis and management [5–8]. Cardiac MRI (CMR) is the reference standard for assessing RV size, systolic function, and mass [9]. Additionally, CMR without anesthesia has been a Class I-IIa indication since 2015 for both initial and serial assessment in children with PH [10,11]. However, sedation requirements in younger children, prolonged examinations, intravenous access for contrast, and substantial hospital resource use limit routine CMR adoption in pediatric PH [12–15].

Disease-specific CMR is now an established component of pediatric cardiac imaging, with consensus guidelines advocating for protocols tailored to specific disease states rather than a single generic examination to improve clinical care, optimize resource utilization, and standardize image acquisition [9,12,16]. For pediatric PH, the guideline highlights the importance of a focused assessment of the RV and pulmonary arteries, as RV size, systolic function, and mass are among the most important prognostic markers in this population [12,17,18]. Recommended CMR measures include RV size, mass, and systolic function as above in addition to cardiac index, pulmonary-to-systemic flow ratio (Qp:Qs), and differential pulmonary blood flow. Additionally, contrast-enhanced CMR angiography and cardiac-gated 3D imaging are recommended to delineate pulmonary arterial and venous anatomy. However, despite these recommendations, CMR practices within this population vary across centers and institutional approaches to pediatric PH CMR have not been published.

Building on this literature, our institutional PH and CMR teams developed a focused pediatric PH CMR protocol to standardize image acquisition and reduce procedural burden. We evaluated the impact of this focused pediatric PH CMR protocol on exam duration, protocol adherence, contrast administration, and anesthesia use and present the rationale for its development.

METHODS

Study design

This single-center retrospective study included children with PH (age >3 months and <21 years) who underwent a clinical CMR between January 2018 to December 2025. CMR was typically performed at baseline evaluation and every 1–2 years thereafter, depending on PH severity, consistent with published guidelines [10–12]. All patients required prior hemodynamic confirmation of PH, defined as patients >3 months of age with mean pulmonary arterial pressure (mPAP) >20 mmHg, indexed pulmonary vascular resistance (PVRi) ≥3 WU.m^2, and mean pulmonary capillary wedge pressure (mPCWP) <15 mmHg [17]. The institutional review board approved the study and waived informed consent.

Creation and implementation of a PH CMR protocol

A focused PH CMR protocol (Figure 1) was implemented in late 2022, with further protocol review and PH education of CMR technologists and faculty in January 2024. The protocol assessed cardiac and pulmonary vascular anatomy, biventricular size, function and mass, eccentricity index, systemic and pulmonary cardiac output, and differential pulmonary blood flow. First-time exams targeted <35 minute exam duration and included contrast-enhanced magnetic resonance angiography (MRA) and 3D anatomic imaging when clinically indicated.

Follow-up exams targeted 25–30 minute exam duration and omitted contrast unless indicated (ex: congenital heart disease [CHD]). For children unable to perform breath holds, free-breathing sequences used multiple signal averaging or respiratory triggering. Additional cine and phase contrast sequences were added based on the clinical indication at the discretion of the CMR physician.

Covariates

Patient demographics and clinical characteristics were collected via chart review from the medical record. Age, sex, weight, World Symposium of Pulmonary Hypertension (WSPH) PH group classification, World Health Organization Functional Class (WHO FC), and PH severity at time of CMR were recorded. A standardized PH severity classification system remains to be established but has been traditionally categorized at our institution as follows: mild (systolic RV pressure < 50% of systemic blood pressure), moderate (≥ 50% but < 100%), and severe (≥ 100%). This assessment was based on cardiac catheterization data (preferred) or echocardiographic data within 6 months of CMR. Medication regimen was categorized as no, single, dual, or triple therapy [17].

Recorded CMR examination details included first-time vs. follow-up PH CMR, sedation or general anesthesia use, respiratory approach, contrast administration, and coordination with same-day heart catheterization or another clinically indicated MRI. Exam duration was defined as the interval from the first to last CMR sequence in minutes. Lastly, additional sequences outside of the PH CMR protocol were described, including number, type, and reason (e.g., repeat for image quality vs. protocol deviation).

Analysis methods

Data are presented as n (%) or median (interquartile range [Q1-Q3]), as appropriate. Data will be compared across three eras: era 1 (1/2018-12/2022; pre-protocol implementation), era 2 (1/2023-12/2023; post-protocol implementation), and era 3 (1/2024-12/2025; post-additional education). For specific sub-analyses, certain groups were excluded from these eras. Due to an institutional MR vendor transition and ongoing scanner optimization, exams performed in 2025 (n=28) were excluded from exam duration and sequence count analyses. Additionally, patients who received sedation for MRI (n=43) were excluded from breath-holding analyses. Groups were compared using the Chi-square (Fisher's exact test, if n<5) or the Kruskal Wallis test, as appropriate. Pairwise multiple comparisons were made using the Dunn test. For specific pairwise comparisons between eras, the post-hoc Dunn test p-value is presented. Analyses were performed using STATA 15.1. P-values <0.05 or 95% CI which did not include unity were considered statistically significant.

RESULTS

This cohort included 129 CMR exams in 57 children (median age 12.7 years [IQR 7.9-15.9]) during the study period, including 48 exams in 21 patients in era 1 (2018-2022), 28 exams in 13 patients in era 2 (2023), and 53 exams in 23 patients in era 3 (2024-2025; Table 1, Figure 2A). There were no incomplete or aborted CMR exams across all three eras.

The majority of CMR exams were in patients with WSPH group I pulmonary arterial hypertension (PAH; n=100, 77.5%), including idiopathic PAH (IPAH; n=28, 21.7%), hereditary PAH (HPAH; n=49, 38.0%), and PAH-CHD (n=23, 17.8%) (Table 1). The majority of CMR exams in patients with HPAH were due to a known genetic variant including BMPR2 (n=15), TBX4 (n=8), and SOX17 (n=12), or HHT (n=7) or other genetic syndrome (n=7). Patients with

PAH-CHD included atrioventricular septal defect (n=4), ventricular septal defect (n=13), or d-transposition of the great arteries with associated VSD or coarctation (n=6). All patients with PAH-CHD were repaired except for one patient with Eisenmenger syndrome in the setting of a VSD. Patients with WSPH group III PH (n=29, 22.5%) had a history of bronchopulmonary dysplasia (n=11), chronic lung disease due to congenital diaphragmatic hernia (n=6), interstitial lung disease (n=5), or other lung disease (n=8). Two patients primarily classified as WSPH group III PH had co-morbid CHD including an atrial and ventricular septal defect, respectively. At time of CMR, the majority of patients were WHO FC I/II (n=95, 73.6%), with moderate or severe PH (n=110, 85.3%), and on dual or triple therapy (n=111, 86.0%) (Table 1).

There were several differences in cohort characteristics across eras. Patients were older in era 3 compared to era 1 (median 14.2 years [IQR 9.3-17.1] vs. 10.3 years [IQR 6.2-13.5], $p<0.001$) in the setting of an aging cohort and changing case mix across eras. Although not statistically significant, the proportion of patients who were WHO FC III/IV (20.8% vs. 30.2%; $p=0.54$) and on triple therapy (56.3% vs. 73.6%; $p=0.17$) increased from era 1 to era 3 (Table 1, 2B).

CMR volume and duration

Over the study period, annual center volume increased from ~10 exams per year in the earliest era to ~26 exams per year in the most recent era (Figure 2A). CMR exam duration significantly decreased after protocol implementation, from a median of 40 minutes [IQR 33–50] in era 1 to 32 minutes [IQR, 27–36] in era 3 ($p=0.003$; Table 2 and Figure 3). This reduction was greater for first-time CMR examinations (11-minute decrease) than for follow-up examinations (4-minute decrease; Table 2).

The majority of non-sedated CMR used breath hold cine acquisition. Free-breathing cine acquisition was used in 9/31 [29.0%] exams in era 1 and 13/35 [37.1%] in era 3 (p=0.75; Table 2). Children who performed breath holds were generally older than those who underwent free-breathing acquisition, although age difference were not statistically significant within eras (Table 2; p>0.05 for patient age comparisons within eras). Most CMR exams (n=78/129, 60.5%) were combined with a same-day heart catheterization procedure with no observed difference in exam duration (data not presented). Only 5/129 (3.9%) were combined with another clinically indicated MRI.

Protocol adherence and sequence analyses

The median number of CMR sequences and variability decreased from eras 1 to 3 (19 [IQR 16-23] vs. 17 [IQR 16-18], p=0.01; Table 2, Figure 4A). Similarly, the number of non-protocol sequences per exam decreased from eras 1 to 3 (5 [IQR 3-8] vs. 2 [IQR 1-3], p<0.001; Table 2, Figure 4B). Overall, this reduction was related to decreased number of sequences added at the discretion of the CMR physician across eras, whereas the number of sequences repeated for quality assurance remained consistent (Table 2, Figure 4B). The most common types of non-protocol sequences included tissue characterization and delayed gadolinium enhancement in era 1 and additional 3D imaging or 4D flow in eras 2 and 3 (data not presented).

Contrast and sedation

Across eras, contrast administration decreased from eras 1 to 3 (n=26/48 [54.2%] vs. 16/53 [30.2%], p=0.007), which mirrored decreased frequency of first-time CMRs across eras (Table 2). The use of contrast slightly trended down for follow-up CMR exams during the study period (4/16 [25.0%] vs. 7/39 [17.9%], p=0.80). The use of sedation for CMR studies remained consistent across eras (Table 2); however, the number of patients under 8 years of age who

received sedation not as part of a combined catheterization procedure decreased from eras 1 to 3 (2 patients vs 0 patients, p=1.00).

DISCUSSION

In pediatric PH, CMR is indicated as a crucial, non-invasive modality for serial assessment of the RV as part of comprehensive risk stratification and management [3,18,19]. Barriers to implementation of CMR in pediatric PH are diverse and include sedation needs in younger children, patient tolerance of prolonged exams, intravenous access needs for and risks associated with contrast use, and increased hospital resource utilization [19]. In collaboration between the PH and CMR teams, a focused PH CMR protocol was implemented which resulted in shorter exam duration, more standardized image acquisition, and reduced contrast administration despite increasing patient complexity and center volume. Further longitudinal follow-up is needed to determine whether focused protocols significantly reduce anesthesia use in younger children. Our findings support disease-specific CMR protocols as a practical strategy for routine and serial non-invasive RV surveillance in pediatric PH.

We found that focused, PH-specific CMR was feasible and efficient at our institution. Protocol implementation improved standardized image acquisition with limited provider variation and use of discretionary sequences which reduced the total number of sequences acquired and overall exam duration. Our experience provides practical evidence that disease-specific CMR protocols can translate guideline recommendations into more consistent and efficient clinical practice, mirroring an approach that is increasingly adopted across a broad range of pediatric cardiovascular indications including CHD, acquired heart disease, and cardio-oncology cardiomyopathy [9,12,16]. Notably, the reduction in contrast use during the study

period was driven in part by a shift toward a great proportion of follow-up CMR exams, which are performed without contrast per our protocol except for specific clinical indications (e.g., CHD in the PAH-CHD cohort and cases of IPAH who had undergone the Potts shunt procedure). There is a dose-dependent, cumulative risk of gadolinium deposition in multiple organs, including the brain, with serial exposure to this contrast agent [20–22]. While the exact significance of such cumulative deposition remains uncertain, the CMR community aims to reduce gadolinium exposure in all children with careful consideration of contrast indications as part of disease-specific CMR [9,13,23,24]. Additionally, the emphasis on free-breathing cine acquisition techniques and shortened exam duration did not reduce our institutional sedation needs, though this may reflect the high utilization of same-day CMR and cardiac catheterization under a single general anesthesia event in recent years. Especially in pediatric PH, sedation is associated with inherent risk and requires anesthesia expertise for close cardiopulmonary and hemodynamic monitoring [12,15]. Additional investigation should evaluate strategies to decrease sedation requirements to improve access to PH CMR.

Beyond reducing exam duration and resource utilization, our program aimed to standardize the acquisition of clinically relevant information and begin to create a reproducible minimum dataset in pediatric PH. A minimum cardiac imaging dataset is an indication-specific CMR protocol focused on the anticipated exam goal and clinical needs of a given patient population, a concept most extensively developed to date in CHD and cardiomyopathy [25]. These standardization efforts are central to quality control and consistency across scanners and interpreting physicians, longitudinal clinical follow-up, and multicenter research collaborations. While the minimum dataset within pediatric PH remains to be established, we aim to share our clinical reasoning for the development of our PH CMR protocol that focuses on clinically

relevant and prognostically useful CMR metrics. In pediatric PH, RV size, systolic function, and hypertrophy by CMR are predictive of transplant-free survival and incorporated into risk stratification models to guide long-term management [17–19,26,27]. The eccentricity index correlates with right ventricular afterload and adds a helpful hemodynamic metric to CMR [19,28,29]. Additionally, calculation of differential pulmonary blood flow is valuable for pulmonary vascular resistance calculations in the catheterization laboratory, particularly in cases with distal or long-segment pulmonary artery stenosis and pulmonary vein stenosis [9]. CMR-derived cardiac index and Qp:Qs are valuable metrics of overall cardiac function and shunts and may offer greater reliability than cardiac catheterization-derived estimates, which can depend on assumptions inherent to the Fick principle [30]. Lastly, for children with CHD or surgical palliation such as the Potts shunt, additional imaging techniques may be indicated for a complete CMR evaluation. These concepts comprise the standardized reporting metrics at our institution.

As part of our minimum imaging dataset, we did not incorporate parametric, late gadolinium enhancement (LGE), or 4D-flow imaging techniques into our protocol. LGE and T1 mapping are useful for tissue characterization and non-invasive assessment of myocardial fibrosis with predictive utility in CHD [31]. However, given the high prevalence of LGE and elevated native T1 in adults with PH with no additive prognostic value as well as the need to place an IV and administer gadolinium contrast for LGE, we opted not to include these sequences [7,19,32,33]. Lastly, 4D-Flow (4DF) provides time-resolved, three-dimensional quantification of blood flow throughout the cardiovascular system and has the potential to describe more granular properties of pulmonary vasculature, such as vorticity which correlates with invasive mean pulmonary artery pressures measurements [34,35]. However, at the time of

protocol implementation, the time needed for 4DF sequence acquisition and post-processing limited utility and integration of this technique into our standard clinical practice.

The findings of this study should be interpreted in the setting of several limitations. Notably, this was a real-world single-center study evaluating practice within a rare pediatric disease and thus our cohort was small and dependent on the evolving annual case mix and referral patterns. Over the last 2-3 years of the study period, only one child <8 years of age presented with new onset PAH and underwent CMR at our institution, which, in part, contributed to the increasing cohort age in the later eras. Secondly, given the institutional interest from the PH team to increase CMR volume in a feasible manner for their patients, there is inherent bias in the increasing CMR exam volume observed across eras. Finally, while our data demonstrated the practical feasibility of a disease-specific PH CMR protocol, we did not assess its diagnostic adequacy and clinical satisfaction, impact on clinical practice, or the potential for missed findings. Future studies aimed at validating the proposed minimum dataset against medical management decisions and clinical outcomes are important to address this gap.

CONCLUSION

Implementation of a focused PH CMR protocol was associated with significantly reduced overall study duration and contrast administration despite increasing patient complexity and center volume. Our findings suggest that a focused, indication-specific CMR protocol is a feasible, practical approach to improve standardization of image acquisition as part of routine and serial RV surveillance in pediatric PH.

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Table 1. Patient Characteristics

	Total (n=129)	**Era 1** (n=48)	**Era 2** (n=28)	**Era 3** (n=53)	*p-value*
Age (*yr*)	12.7 (7.9-15.9)	10.3 (6.2-13.5)	13.3 (9.9-16.1)*	14.2 (9.3-17.1)*	0.002
Sex (*female*)	84 (65.1%)	30 (62.5%)	16 (57.1%)	38 (71.7%)	0.38
Weight (*kg*)	41.0 (23.1-56.0)	25.2 (19.5-52.7)	45.6 (27.7-56.5)*	46.0 (27.2-59.6)*	0.01
WSPH PH group					0.34
Group I PAH	100 (77.5%)	34 (70.8%)	22 (78.6%)	44 (83.0%)	
IPAH	28 (21.7%)	10 (20.8%)	7 (25.0%)	11 (20.8%)	
HPAH	49 (38.0%)	17 (35.4%)	8 (28.6%)	24 (45.3%)	
PAH-CHD	23 (17.8%)	7 (14.6%)	7 (25.0%)	9 (17.0%)	
Group III PH	29 (22.5%)	14 (29.2%)	6 (21.4%)	9 (17.0%)	
BPD	11 (8.5%)	7 (14.6%)	1 (3.6%)	3 (5.7%)	
CDH	6 (4.7%)	4 (8.3%)	1 (3.6%)	1 (1.9%)	
ILD	5 (3.9%)	1 (2.1%)	2 (7.1%)	2 (3.8%)	
Other†	8 (6.2%)	3 (6.3%)	2 (7.1%)	3 (5.7%)	
WHO FC					0.54
I/II	95 (73.6%)	38 (79.2%)	20 (71.4%)	37 (69.8%)	
III/IV	34 (26.4%)	10 (20.8%)	8 (28.6%)	16 (30.2%)	
PH severity					0.44
Mild	19 (14.7%)	7 (14.6%)	7 (25.0%)	5 (9.4%)	
Moderate	82 (63.6%)	30 (62.5%)	15 (53.6%)	37 (69.8%)	
Severe	28 (21.7%)	11 (22.9%)	6 (21.4%)	11 (20.8%)	
Medication regimen					0.17
None	7 (5.4%)	4 (8.3%)	3 (10.7%)	-	
Single	11 (8.5%)	5 (10.4%)	2 (7.1%)	4 (7.6%)	
Dual	30 (23.3%)	12 (25.0%)	8 (28.6%)	10 (18.9%)	
Triple	81 (62.8%)	27 (56.3%)	15 (53.6%)	39 (73.6%)	

Data presented as median (interquartile range) or n (%). Groups were compared using the Chi-square (Fisher's exact test, if n<5) or the Kruskal Wallis test, as appropriate. Pairwise multiple comparisons were made using the Dunn test, with *indicating p<0.05 relative to Era 1 and **indicating p<0.05 relative to Era 2. †Other group III PH diagnoses included subglottic stenosis with chronic aspiration, bronchiolitis obliterans, pulmonary hypoplasia, congenital pulmonary airway malformation.

BPD = bronchopulmonary dysplasia, CDH = congenital diaphragmatic hernia; HHT = hereditary hemorrhagic telangiectasia, HPAH = hereditary pulmonary arterial hypertension, ILD = interstitial lung disease, IPAH = idiopathic pulmonary arterial hypertension, PAH = pulmonary arterial hypertension, PAH-CHD = pulmonary arterial hypertension associated with congenital heart disease, PH = pulmonary hypertension, WHO FC = World Health Organization Functional Class, WSPH = World Symposium of Pulmonary Hypertension

Table 2. Patient Characteristics

	Total (n=129)	**Era 1** (n=48)	**Era 2** (n=28)	**Era 3** (n=53)	*p-value*
First time CMR	56 (43.4%)	32 (66.7%)	10 (35.7%)	14 (26.4%)	<0.001
Exam duration (*min*)†	36 (30-47)	40 (33-50)	40 (31-47)	32 (27-36)*/**	0.02
First time CMR duration (*min*)†	41 (32-51)	42 (33-52)	45 (36-53)	31 (25-36)*/**	0.09
Follow-up CMR duration (*min*)†	34 (29-42)	36 (33-49)	35 (30-41)	32 (27-35)	0.33
Free-breathing cine technique‡	28 (32.6%)	9 (29.0%)	6 (30.0%)	13 (37.1%)	0.75
Age (*yr*)‡	13.5 (11.9-16.1)	13.3 (7.3-13.9)	14.9 (12.7-17.1)	13.6 (12.8-15.9)	0.39
Breath-hold cine technique ‡	58 (67.4%)	22 (71.0%)	14 (70.0%)	22 (62.9%)	0.75
Age (*yr*)‡	14.4 (12.1-17.2)	12.1 (10.3-14.7)	13.9 (12.2-16.2)	16.9 (14.2-18.1)*/**	0.001
Contrast administration	54 (41.9%)	26 (54.2%)	12 (42.9%)	16 (30.2%)	0.007
For follow-up CMRs	15/73 (20.5%)	4/16 (25.0%)	4/18 (22.2%)	7/39 (17.9%)	0.80
GA/Sedation	43 (33.3%)	17 (35.4%)	8 (28.6%)	18 (34.0%)	0.82
GA/Sedation if <8 yoa	25/33 (75.8%)	12/17 (70.6%)	4/5 (80.0%)	9/11 (81.8%)	0.86
GA/Sedation if <8yoa without cath	2/10 (20%)	2/7 (28.6%)	0/1 (0%)	0/2 (0%)	1.00
Sequences/exam†	18 (16-22)	19 (16-23)	20 (18-22)	17 (16-18)*/**	0.02
Non-protocol sequences/exam†	4 (2-7)	5 (3-8)	5 (3-6)	2 (1-3)*/**	<0.001
Indications for non-protocol sequences					
Quality assurance†	2 (1-3)	1 (1-2)	3 (2-4)	2 (1-3)	0.22
Discretion of CMR attending†	5 (3-7)	5 (3-8)	5 (3-7)	2 (2-5)*/**	0.06

Data presented as median (interquartile range) or n (%). Groups were compared using the Chi-square (Fisher's exact test, if n<5) or the Kruskal Wallis test, as appropriate. Pairwise multiple comparisons were made using the Dunn test, with *indicating p<0.05 relative to Era 1 and **indicating p<0.05 relative to Era 2. †Sequence and exam duration analyses exclude 2025 exams (n=29) as delineated in the Methods. ‡Free-breathing and breath-hold analyses exclude sedated patients (n=43).

CMR = cardiac magnetic resonance imaging, GA = general anesthesia, MRI = magnetic resonance imaging, PC = phase contrast

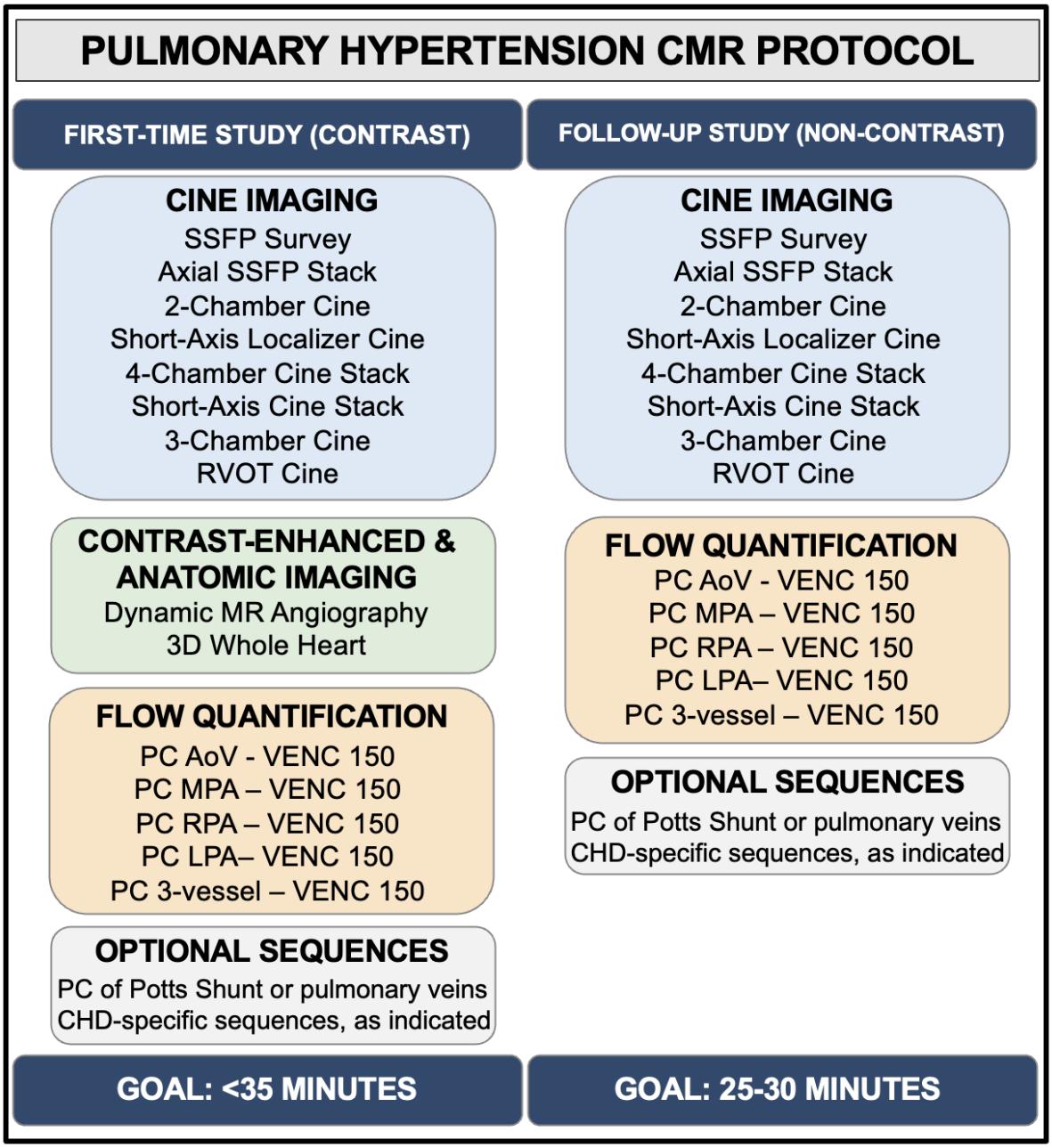


Fig 1 Pulmonary Hypertension CMR Protocol. A short, focused PH CMR protocol was created with the goals of anatomic delineation and assessment of biventricular size, function and mass, systemic and pulmonary cardiac output, and differential pulmonary blood flow. All first time studies (left column) included contrast administration for magnetic resonance angiography and anatomic delineation, if clinically indicated. Follow-up studies were performed without contrast administration, unless clinically indicated. Optional sequences based on clinical indication are included at the bottom. *AoV = aortic valve, CHD = congenital heart disease, CMR = cardiac magnetic resonance imaging, LPA = left pulmonary artery, MPA = main pulmonary artery, PC = phase contrast, PH = pulmonary hypertension, RPA = right pulmonary artery, RVOT = right ventricular outflow tract, SSFP = steady state free precession*

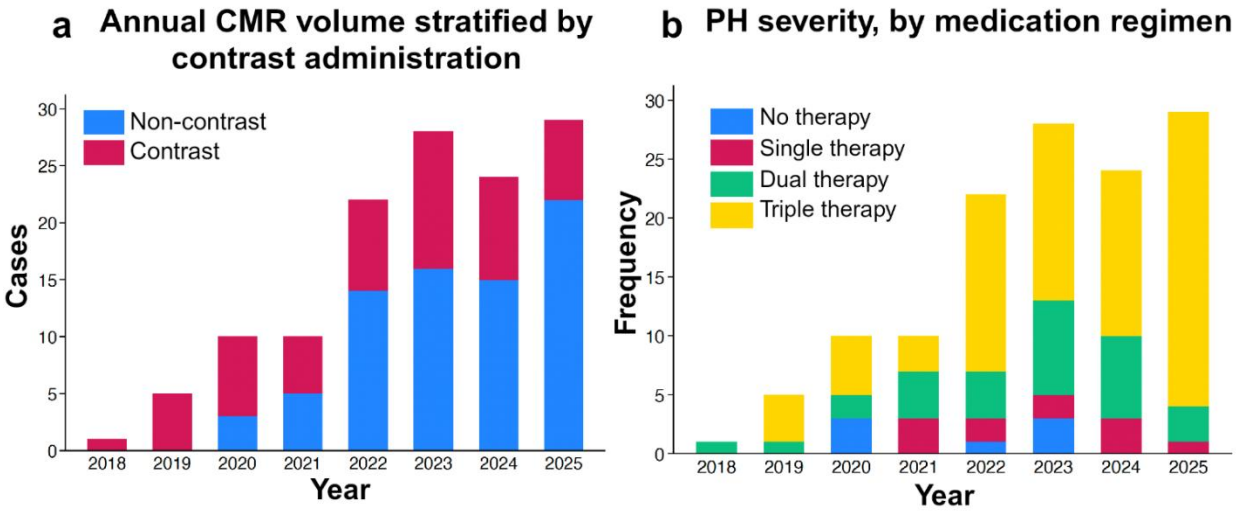


Fig 2 Annual CMR volume and PH medication regimen across the study period. a. Annual CMR volume for contrast (red) and no-contrast (blue) studies. b. PH medication regimen at the time of exam: none (blue), single (red), dual (green), or triple (yellow) PH therapy. *CMR = cardiac magnetic resonance imaging, PH = pulmonary hypertension*

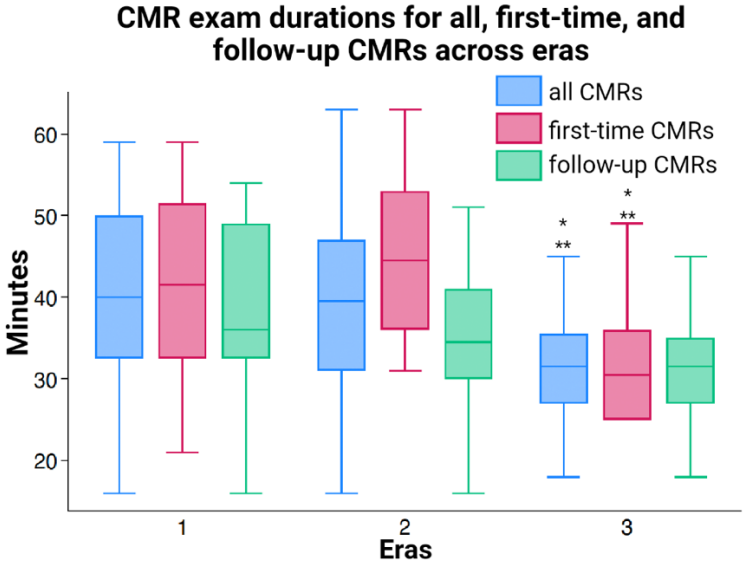


Fig 3 CMR exam duration. CMR exam duration for all exams (blue), first-time exams (red), and follow-up exams (green) in minutes, by era. *indicating p<0.05 relative to Era 1 and **indicating p<0.05 relative to Era 2. *CMR = cardiac magnetic resonance imaging*

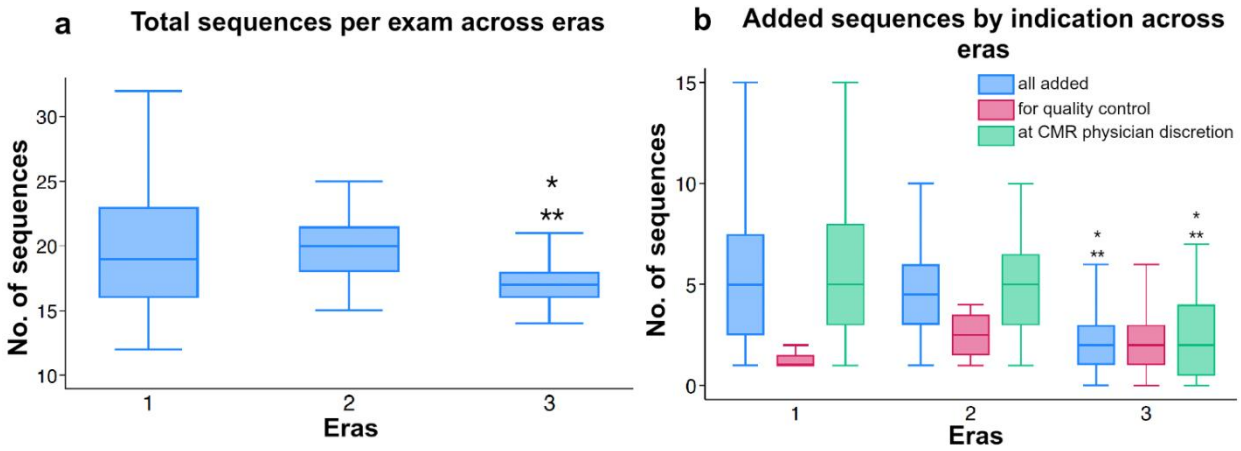


Fig 4 Sequences per CMR Exam by era. a. Number of total sequences per CMR exam by era. b. All added sequences (blue), added sequences for quality control (red), and added sequences at the discretion of the CMR physician (green) by era.*indicating $p<0.05$ relative to Era 1 and **indicating $p<0.05$ relative to Era 2. *CMR = cardiac magnetic resonance imaging*