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ORIGINAL ARTICLE

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Reducing radiation exposure by lowering frame rate in children undergoing cardiac catheterization: A quality improvement study

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Abstract

Introduction: Reduction of radiation dosage in the pediatric cardiac catheterization laboratory (PCL) is important to reduce the risk of its stochastic effect in children with congenital heart disease. Lowering the frame rate would reduce radiation dosage possibly at the expense of image quality, potentially resulting in higher fluoroscopic time and procedural complication rate.

Methods: The data were retrospectively analyzed in three eras: era 1 (n = 234), cineangiography 30 frames/sec (f/s) and fluoroscopy 15 pulse/sec (p/s); era 2 (n = 381), cineangiography 30 f/s and fluoroscopy 6 p/s; and era 3 (n = 328), cineangiography 15 f/s and fluoroscopy 6 p/s. Also, three operators blinded to the frame rate setting evaluated cineangiography image quality. In this study, the impact of lowering the default frame rates on radiation dosage, fluoroscopic time, contrast volume, diagnostic image quality, and complication rates in the PCL was assessed.

Results: Overall radiation dosage progressively declined during these eras (70.0 vs 64.1 vs 36.6 $\mu Gym^2/kg$, $P < .001$) without a difference in significant adverse event rates. There was no significant increase in either fluoroscopy time or contrast volume. There was no difference in the diagnostic image quality between cineangiography 30 and 15 f/s. Lowering the default frame/pulse rates of both fluoroscopy and cineangiography significantly decreased the overall radiation dosage in the PCL. Importantly, fluoroscopy time, contrast volume, and complication rates did not increase while maintaining diagnostic image quality.

Conclusion: This quality improvement project proved successful in lowering radiation dosage without compromising the efficacy and safety of catheterizations.

KEYWORDS
children, cineangiography, complication, fluoroscopy, frame rate, radiation dosage

1 | INTRODUCTION

Children with congenital heart disease (CHD) require multiple x-ray imaging studies including chest radiography, computed tomography, and cardiac catheterization. Those with complex CHD, single ventricle physiology or post–cardiac transplantation receive even higher cumulative radiation exposure, mainly from cardiac catheterization.[1-4] This increased exposure may increase the lifetime risk of cancer in such patients.[5] Operators should keep radiation exposure as low as reasonably achievable

(ALARA) without compromising diagnostic integrity and procedural safety.[6,7] Lowering the frame/pulse rates of cineangiography and fluoroscopy is one of the approaches for dose optimization in the cardiac catheterization laboratory.[7] Furthermore, lowering the pulse rate of fluoroscopy alone can significantly reduce radiation dosage in the pediatric cardiac catheterization laboratories (PCL).[8-12] However, the impact of lowering the frame rate of cineangiography on radiation dosage and procedural safety of catheterization has not been well studied in the PCL.

In the PCL at a tertiary children's hospital, a radiation reduction protocol using low default frame/pulse rates of cineangiography and fluoroscopy was implemented as a quality improvement project. The hypothesis was that significant reduction of radiation dosage would be achieved without compromising the diagnostic integrity and procedural safety of catheterization using low default frame/pulse rates.

2 | METHODS

This was a retrospective study conducted at Children's Hospital of Michigan. The study period was from January 2014 to May 2015. Radiation reduction measures were implemented stepwise. In June 2014, the default pulse rate of fluoroscopy was reduced from 15 to 6 pulse/sec (p/s). In December 2014, the default frame rate of cineangiography was reduced from 30 to 15 frame/sec (f/s). Operators (3 interventional cardiologists and 1 electrophysiologist) were allowed to increase the frame/pulse rates during the catheterizations if clinically indicated. Angiographic systems were Axiom Artis (Siemens Medical Solutions, Erlangen, Germany) with biplane flat panels and no capability of rotational angiography. There were no upgrades to our angiographic systems. Catheterizations were performed with the use of an antiscatter grid with no change in the setting of frame/pulse width and voltage. Other radiation optimization methods (collimation, minimizing the distance between the patient and the flat panel and the largest field of view) were used by operators as much as possible. The air gap method was not used.

The radiation physicist checked the angiographic systems biannually and made no major change in the settings of fluoroscopy or cineangiography during the study period. For each cineangiography, contrast volume, injection speed, pressure per square inch, rise times, and angiographic catheters were at the discretion of operators. Storing fluoroscopic images were often used for simple venography and storing interventional procedures include balloon angioplasty, valvuloplasty, and stent placement. The data were collected before and after these changes. The study period was divided into three eras: era 1 (January to May 2014: cineangiography 30 f/s and fluoroscopy 15 p/s), era 2 (June to November 2014: cineangiography 30 f/s and fluoroscopy 6 p/s), and era 3 (December 2014 to May 2015: cineangiography 15 f/s and fluoroscopy 6 p/s). The inclusion criteria were patients undergoing cardiac catheterization in the PCL. The exclusion criteria were electrophysiology studies utilizing no-fluoroscopic technique, cardioversion, or loop recorder implantation. This study was approved by the Wayne State University Institutional Review Board.

Data were collected on age, gender, weight, height, body surface area, presence of a trainee, underlying cardiac diagnosis, major procedural types (diagnostic, interventional, transplant biopsy with and without coronary angiography, electrophysiology study, and hybrid procedure), radiation dosage (dose area product [μGym^2], skin dose [mGy]), fluoroscopy time (minute), contrast volume (mL), and significant adverse event. Significant adverse events were those defined by Nykanen et al.[13] Body weight was used to index dose area product ($\mu Gym^2/kg$) and contrast volume (mL/kg).[14] Patients with cardiac transplantation, single ventricle physiology, complex pulmonary artery, and right ventricular outflow pathology require multiple cardiac catheterizations. Hence, they are at higher risk for cumulative radiation exposure, and thus would potentially derive the greatest benefits from the radiation reduction protocol. Accordingly, two procedure groups were created to assess the effect of the radiation reduction protocol across the eras in these high-risk patients: (1) single ventricle diagnostic catheterizations with and without coiling of collaterals, such as pre-hemi Fontan and pre-Fontan catheterizations; (2) complex interventions consisting of angioplasty and stent placement in pulmonary artery and right ventricle to pulmonary artery conduit and transcatheter pulmonary (Melody) valve implantation.

2.1 | Assessment of cineangiography image quality

Diagnostic imaging quality was compared between era 2 (cineangiography 30 f/s) and era 3 (15 f/s). Due to the heterogeneous nature of cardiac diagnosis and procedure types in the PCL, 18 age- and heart rate-matched cases were selected from each era: patent ductus arteriosus (n = 2), pulmonary artery stenting (2), atrial septal defect device closure (2), coarcation of the aorta stenting (2), transcatheter pulmonary valve implantation (2), pre–hemi Fontan catheterization (2), pre-Fontan catheterization (2), balloon pulmonary valvuloplasty (2), and transplant biopsy with coronary angiography (2). Three interventional cardiologists who were blinded to the radiation protocol graded the quality of the images using a grading system described by Ebrahimi et al: (1) good to excellent (defined as more than adequate to make diagnostic interpretation); (2) adequate (defined as adequate to make diagnostic interpretation); and (3) inadequate (defined as inadequate to make diagnostic interpretation).[15] Specifically, images were considered inadequate when the target lesion was not visualized or could not be measured accurately.

2.2 | Statistical analysis

Data were analyzed in each era, stratified by major procedure types and high-risk procedure groups. Median and interquartile range was used for continuous variables that did not follow normal distribution. Categorical variables were expressed as frequency (percent).

TABLE 1 Patient and procedural characteristics

	Era 1 (*n* = 234) Jan 2014–May 2014 Median [IQR] or *n* (%)	Era 2 (*n* = 381) Jun 2014–Nov 2014 Median [IQR] or *n* (%)	Era 3 (*n* = 328) Dec 2014–May 2015 Median [IQR] or *n* (%)	*P* value
Cineangiography (f/s)	30	30	15	NA
Fluoroscopy (p/s)	15	6	6	NA
Age (years)	9.8 [1.5-20.2]	7.8 [1.0-16.9]	11.5 [2.6-19.6]	.041
Gender (male)	109 (47%)	163 (43%)	164 (50%)	.157
Weight (kg)	28.6 [8.5-63.9]	26.8 [9.6-64.3]	38.1 [13.3-71.5]	.017
Height (cm)	132 [69-165]	131 [75-163]	143 [88-168]	.017
Body surface area (m^2)	1.04 [0.39-1.71]	1.02 [0.43-1.70]	1.25 [0.54-1.81]	.015
Trainee present	109 (47)	163 (43)	164 (50)	.157
Major procedure types				
Diagnostic	51 (21.8)	104 (27.3)	63 (19.2)	.041
Interventional	109 (46.6)	166 (43.6)	173 (52.7)	
Transplant	23 (9.8)	27 (7.1)	35 (10.7)	
Electrophysiology	48 (20.5)	75 (19.7)	55 (16.8)	
Hybrid	3 (1.3)	9 (2.3)	2 (0.6)	

Abbreviations: f/s, frame per second; p/s, pulse per second.

Nonparametric tests were used to compare the variables between eras. Chi-square tests were used for categorical variables. Line graphs of monthly median radiation dosage were depicted. Box plots were used to compare the radiation dosage between eras, stratified by major procedure types. A $P < .05$ was considered statistically significant. Statistical analysis was performed using SPSS version 24 (IBM, Chicago, Illinois).

3 | RESULTS

3.1 | Patient and procedure characteristics

The study cohort consisted of 943 catheterizations: era 1 (*n* = 234), era 2 (381), and era 3 (328), of which 218 were diagnostic, 448 interventional, 85 transplant biopsies with and without coronary angiography, 178 electrophysiology studies, and 14 hybrid procedures. There were slight differences in the case mixtures of age, body size, and major procedure types between eras (Table 1). The median duration of cineangiography was 4.5 seconds (interquartile range 2.6 to 6.4) in our cohort.

3.2 | Overall radiation dosage

There was a significant reduction in radiation dosage with the lowering of frame/pulse rate of cineangiography and fluoroscopy (Table 2A-C). Median radiation dosage decreased by approximately 50% from era 1 to 3 (70.0 to 36.6 $\mu Gym^2/kg$). Lowering the frame rate of cineangiography had a higher impact on the reduction of radiation dosage than decreasing the pulse rate of fluoroscopy as indicated by the greater drop in the total radiation dosage between eras 2 and 3 compared to the drop from era 1 to 2. Fluoroscopy time and contrast volumes were lower in era 3 (Table 2D). A line graph of monthly trends (Figure 1A) showed the decline in radiation dosage of overall, in cineangiography, and fluoroscopy techniques. Box-plots showed a significant reduction in the overall radiation dosage in era 3 (Figure 2A). In era 3, the frame rate of cineangiography increased from 15 to 30 f/s during the procedure in 23/328 (7%) cases based on the operators' discretion. The majority of these were young infants having high heart rates and undergoing interventional procedures such as device/coil closure of patent ductus arteriosus, pulmonary artery stent implantation or angioplasty, and valvuloplasty (Supplementary Table S1).

3.3 | Radiation dosage stratified by procedure type and groups

Age and weight were similar between eras when the procedures were stratified by major procedure types. In all the major procedure types, radiation dosage ($\mu Gym^2/kg$) significantly declined through the eras, whereas there was no increase in fluoroscopy time or contrast use in era 3 (Table 3). A line graph of monthly trends (Figure 1B) showed the decline of radiation dosage in each major procedure type. Box plots showed a consistent reduction in radiation dosage in era 3, stratified by major procedure types (Figure 2B).

Comparison of radiation dosage before and after the QI project showed a significant impact on high-risk patient groups and interventions. The median radiation dosage ($\mu Gym^2/kg$) in transplant

TABLE 2 Overall radiation dosage

	Era 1 (*n* = 234)	Era 2 (*n* = 381)	Era 3 (*n* = 328)	*P* value
	Median [IQR]	Median [IQR]	Median [IQR]	
(A) Dose area product (μGym²)				
Total (μGym²)	1457 [504-5621]	1275 [463-4096]	985 [345-2797]	.004
AP plane	820 [204-2634]	591 [224-1792]	555 [209-1374]	.046
Lateral plane	561 [183-2270]	619 [198-1998]	349 [106-1535]	<.001
Cineangiography total (μGym²)	517 [171-1964]	534 [202-1965]	305 [60-1142]	<.001
AP plane	222 [72-1002]	236 [74-828]	141 [20-598]	.004
Lateral plane	265 [75-1356]	295 [95-1157]	173 [24-657]	<.001
Fluoroscopy total (μGym²)	614 [182-2815]	462 [150-1557]	484 [159-1470]	.044
AP plane	325 [98-1551]	224 [85-869]	296 [102-848]	.061
Lateral plane	180 [32-744]	121 [29-524]	115 [29-498]	.074
(B) Dose area product indexed by body weight (μGym²/kg)				
Total (μGym²/kg)	70.0 [37.3-135]	64.1 [36.5-113]	36.6 [18.3-69.6]	<.001
AP plane	39.5 [17.5-67.6]	30.0 [16.1-51.7]	18.7 [9.9-38.6]	<.001
Lateral plane	28.3 [15.7-69.2]	31.1 [15.3-56.7]	14.5 [5.9-31.4]	<.001
Cineangiography total (μGym²/kg)	33.2 [12.2-78.8]	37.5 [13.5-72.5]	16.8 [2.8-39.8]	<.001
AP plane	15.6 [3.8-35.4]	15.5 [5.1-47.9]	7.0 [1.0-17.8]	<.001
Lateral plane	17.3 [6.9-43.3]	19.7 [6.4-39.6]	9.1 [1.2-20.7]	<.001
Fluoroscopy total (μGym²/kg)	30.8 [16.7-55.9]	21.3 [11.5-39.2]	17.3 [9.2-30.9]	<.001
AP plane	16.9 [7.6-37.5]	12.6 [5.5-25.8]	10.2 [5.0-19.1]	<.001
Lateral plane	8.2 [3.0-20.7]	6.8 [2.4-16.1]	4.6 [1.8-10.9]	<.001
(C) Skin dose (mGy)				
Total (mGy)	287 [101-659]	234 [99.3-540]	150 [63-353]	<.001
AP plane	122 [50-331]	91 [48-244]	75 [34-169]	<.001
Lateral plane	121 [44-346]	118 [44-327]	64 [22-200]	<.001
Cineangiography total (mGy)	103 [45-333]	112 [49-349]	62 [14-213]	<.001
AP plane	44 [17-127]	46 [16-127]	24 [5-75]	<.001
Lateral plane	60 [22-218]	72 [21-225]	31 [5-121]	<.001
Fluoroscopy total (mGy)	104 [40-331]	68 [31-192]	69 [29-171]	.001
AP plane	48 [20-172]	35 [19-95]	39 [17-90]	.04
Lateral plane	36 [7-112]	24 [6-83]	19 [6-64]	.014
(D) Fluoroscopy time (min)				
Fluoroscopy time (min)	18.2 [11.8-27.3]	16.4 [9.7-25.2]	15.3 [9.4-22.5]	0.005
AP plane	11.5 [6.3-19.0]	10.0 [4.8-16.2]	10.1 [4.5-16.2]	0.038
Lateral plane	4.6 [2.1-9.3]	4.2 [1.6-9.6]	3.7 [1.5-7.4]	0.019
Contrast (mL)	28 [10-73]	32 [12-70]	29 [6-70]	0.382
Contrast (mL/kg)	1.9 [0.3-3.2]	1.9 [0.6-3.3]	1.5 [0.1-2.9]	0.004

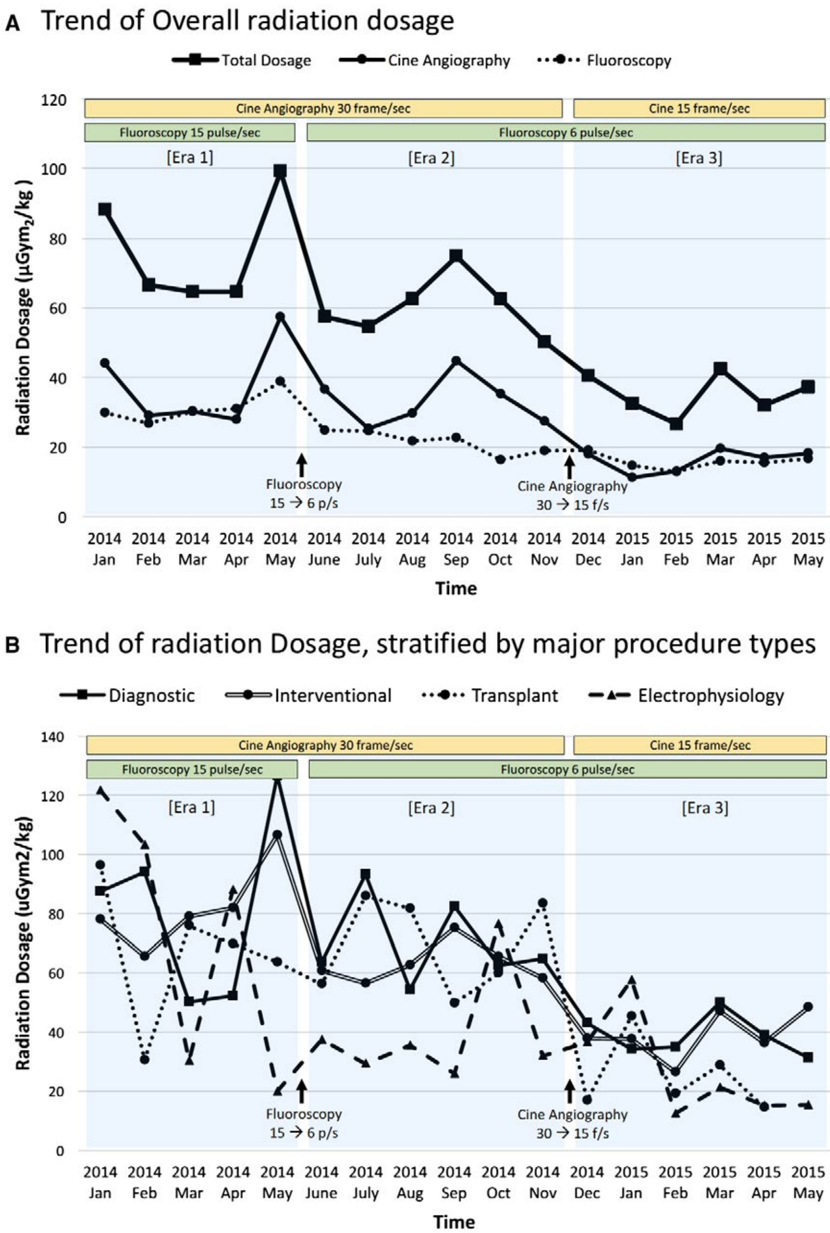

FIGURE 1 Line graphs showing the monthly trend of radiation dosage (µGym^2/kg). (A) Radiation dosage of overall, cineangiography, and fluoroscopy. Era 1 (January to May 2014), cineangiography 30 frame/sec (f/s), fluoroscopy 15 pulse/sec (p/s); era 2 (June to November 2014), cineangiography 30 f/s, fluoroscopy 6 p/s; era 3 (December 2014 to May 2015), cineangiography 15 f/s, fluoroscopy 6 p/S. (B) Radiation dosage, stratified by major procedure types [Colour figure can be viewed at wileyonlinelibrary.com]

biopsy, single ventricle diagnostic catheterizations, and complex interventions was reduced by 62%, 65%, and 61%, respectively (Tables 3 and 4).

3.4 | Cineangiography image quality between 30 and 15 frame/second

Among the 54 catheterization cases reviewed blindly in each group, the majority (96%) were graded “good to excellent” in the 30 f/s group compared to 89% in the 15 f/s group. However, there were no ‘inadequate” cases and all cases were considered either “good to excellent” or “adequate” in the 15 f/s group, whereas 1 case was considered “inadequate” in the 30 f/s group. There was no statistical difference in the image quality grades between eras (Table 5).

3.5 | Complication rates

There was no difference in significant adverse event rates between eras (P = .232). The adverse event rates were: 3.8% (9/234) in era 1; 1.8% (7/381) in era 2; 3.7% (12/328) in era 3.

4 | DISCUSSION

This study describes a successful quality improvement project aimed at reducing radiation dosage by reducing the default frame/pulse rate, without compromising diagnostic integrity or procedural safety in the PCL. The radiation reduction protocol decreased the overall median radiation dosage by half. Even with a lower frame rate (15 f/s) of cineangiography, there was no significant decline in diagnostic

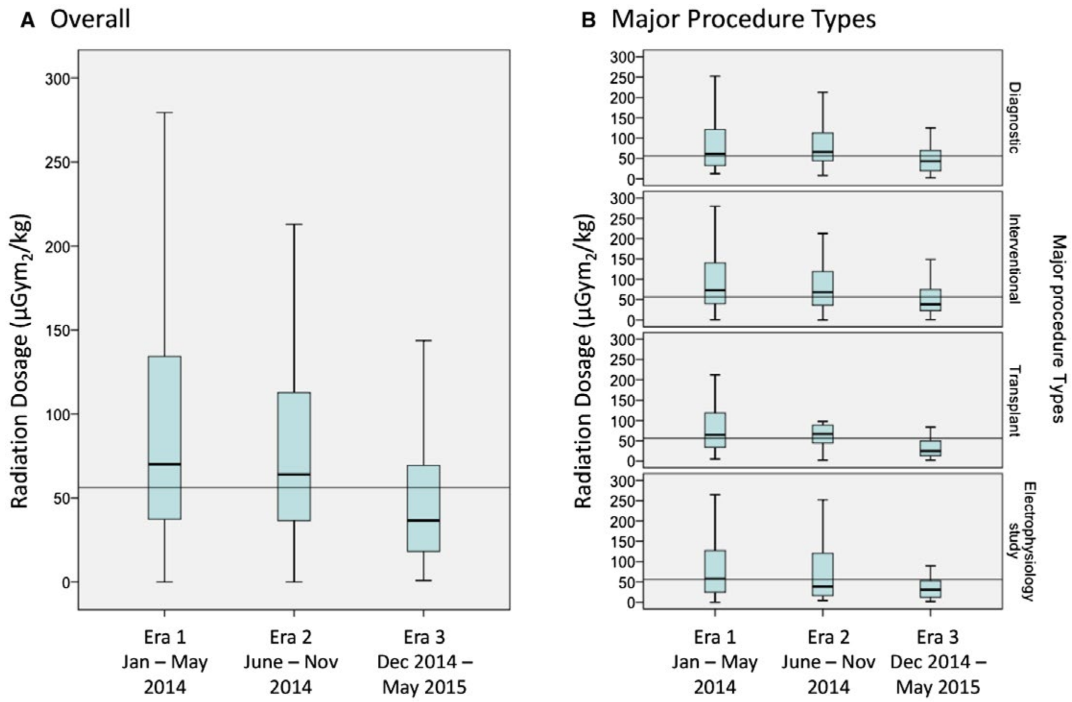

FIGURE 2 Box plots showing the radiation dosage (μGym^2/kg) between three eras, in overall cases (A) and stratified by major procedure types (B). The line shows the overall median radiation dosage of 56.2 μGym^2/kg [Colour figure can be viewed at wileyonlinelibrary.com]

imaging quality. Furthermore, procedural complication rates did not increase with this radiation reduction protocol.

Many children with CHD have a high lifetime radiation exposure from various x-ray imaging studies.[1-3,5] Stochastic effects of such radiation are a real concern and may increase the risk of malignancy. Cardiac catheterization plays an important diagnostic and interventional role but exposes those children to high radiation dosages. Therefore, it is desirable to minimize the radiation exposure to children in the PCL. Furthermore, children with single ventricle physiology, cardiac transplantation, and complex anatomy require multiple cardiac catheterizations, thereby receiving high cumulative radiation exposure.[1-4] In this study, the overall radiation dosage was significantly decreased by lowering the default frame/pulse rates. This radiation dosage reduction was greater in high-risk patients/procedure groups achieving a reduction of 60% in these cohorts.

With these results, it was important to ensure that procedural safety was not impaired by degraded imaging quality. Lower pulse rate fluoroscopy may impair the visual smoothness of the transition between pulsed fluoroscopic images, thereby blurring moving objects and reducing visibility. It remains unknown how low the pulse rates can be to keep acceptable visibility to perform safe and effective catheterization procedures in the PCL. Previous studies have shown the usefulness of very low pulse rate fluoroscopy in certain procedures in the PCL.[8-11] Sutton et al reported the use of 2-3 p/s fluoroscopy for right heart catheterization with endomyocardial biopsy.[11] Hirematch et al reported the use of 4 p/s fluoroscopy for atrial septal defect device closure.[12] Borik et al reported radiation reduction using a default pulse rate of fluoroscopy at 7.5 p/s.[10] In contrast, our radiation reduction protocol was to lower the default pulse rate to 6 p/s. Operators initially experienced some difficulty with the lower pulse rate imaging but quickly adapted themselves to the new protocol. There were a small number of cases where operators increased the pulse rate of fluoroscopy due to the complexity of the anatomy or for specific interventional procedures. Based on this experience, it is recommended to start with a low default pulse rate of fluoroscopy in all cases and increase the pulse rate if necessary.

The effect of low frame rate of cineangiography on radiation dosage has not been well studied in the PCL. Cineangiography images are obtained at much higher x-ray input for acquisition, providing sufficient quality for single-frame viewing. Cineangiography image frames have higher contrast, sharpness, and less noise. But this comes at the expense of higher radiation dose delivered to patients (radiation level is 10-fold higher than during fluoroscopy). A study by Shah et al[16] in the adult cardiac catheterization laboratory where they randomized 50 patients undergoing coronary angiography to either fluorography or cineangiography revealed that peak skin dose [158.2 vs. 272.5 mGy,—42% relative reduction $P < .001$] and kerma air product [1323 vs. 3451 μGy.m^2—62% relative reduction, $P < .001$] were significantly lower in the fluorography group. This study illustrates the fact that cineangiography does substantially increase the radiation dose delivered to patients. Hence, it is not surprising that our greatest benefit (radiation reduction) was achieved from era 2 to era 3 where we decreased our cineangiography frame rate from 30 to 15fps. In our study, the overall fluoroscopy times was successively less during the three eras despite the fact that the number of cases was higher in eras 2 and 3 compared to era 1. We believe that it may be because of an unmeasured reduction in case complexity. In our study, of 23 studies in which the cineangiography frame rate was

TABLE 3 Radiation dosage stratified by major procedure types

Procedure type		Era 1 median [IQR]	Era 2 median [IQR]	Era 3 median [IQR]	*P* value
Diagnostic	Cases (n)	51	104	63	NA
	Age (years)	3.1 [0.5-14.5]	6.4 [0.5-16.8]	10.5 [1.2-20.0]	.188
	Weight (kg)	15.7 [5.1-61.5]	15.3 [6.9-66.9]	35.8 [8.3-81.0]	.110
	Fluoroscopy time (min)	16. 3[10.5-24.6]	15.1 [9.7-27.4]	15.0 [8.3-19.5]	.317
	Contrast (mL/kg)	2.0 [1.2-3.4]	2.5 [1.2-3.7]	1.6 [0.9-2.9]	.012
	Radiation dosage (µGym^2)	835 [306-3010]	1045 [362-3567]	779 [301-4111]	.586
	Radiation dosage (µGym^2/kg)	61.2 [32.7-122]	65.6 [43.8-113]	43.0 [19.7-69.3]	<.001
	Radiation dosage (mGy)	144 [92-482]	204 [97-505]	129 [47-625]	.194
Interventional	Cases (n)	109	166	173	NA
	Age (years)	9.8 [1.5-20.9]	6.9 [0.8-17.8]	8.3 [2.4-19.8]	.342
	Weight (kg)	26.8 [8.4-65.3]	20.8 [9.6-58.8]	25.9 [11.6-67.6]	.285
	Fluoroscopy time (min)	20.0 [13.0-29.3]	18.4 [11.5-25.7]	16.5 [9.9-27.0]	.096
	Contrast (mL/kg)	2.2 [0.3-3.5]	2.1 [0.6-3.6]	2.2 [0.6-3.4]	.931
	Radiation dosage (µGym^2)	1443 [553-5245]	1251 [447-3297]	1123 [359-2785]	.047
	Radiation dosage (µGym^2/kg)	72.9 [39.3-141]	68.2 [35.8-119]	38.6 [22.6-165]	.001
	Radiation dosage (mGy)	302 [130-672]	243 [113-550]	176 [78-353]	.001
Transplant biopsy with and without coronary angiography	Cases (n)	23	27	35	NA
	Age (years)	11. 7 [7.6-15.2]	10.1 [6.2-15.2]	11.3 [5.7-18.1]	.923
	Weight (kg)	28.6 [22.5-55.7]	31.5 [21.8-55.2]	33.5 [18.0-72.0]	.951
	Fluoroscopy time (min)	19.4 [15.2-26.9]	12.9 [9.6-16.4]	13.1 [9.1-18.1]	.001
	Contrast (mL/kg)	1.2 [0.2-2.2]	1.6 [1.0-2.2]	0.7 [0-1.5]	.010
	Radiation dosage (µGym^2)	1728 [1140-4957]	1455 [961-4347]	913 [212-2747]	.031
	Radiation dosage (µGym^2/kg)	64.8 [30.6-121]	66.8 [44.1-91.1]	24.7 [12.4-50.2]	.001
	Radiation dosage (mGy)	334 [140-828]	337 [172-540]	150 [41-387]	.014
Electrophysiology study	Cases (n)	25	40	49	NA
	Age (years)	20. 8 [12.1-33.2]	14.0 [3.6-24.6]	16.7 [10.9-24.1]	.091
	Weight (kg)	62.5 [46.4-71.5]	66.3 [44.9-71.9]	55.0 [38.6-75.1]	.634
	Fluoroscopy time (min)	14.6 [5.6-22.5]	12.3 [9.3-24.1]	14.8 [8.5-19.1]	.898
	Contrast (mL/kg)	0.1 [0-0.4]	0.1 [0-0.4]	0.1 [0-0.1]	.406
	Radiation dosage (µGym^2)	3712 [767-9976]	2483 [912-8900]	1282 [575-2811]	.022
	Radiation dosage (µGym^2/kg)	58.1 [22.3-137]	38.3 [14.8-121]	30.7 [12.5-53.4]	.018
	Radiation dosage (mGy)	311 [75-956]	246 [80-827]	126 [52-308]	.028

TABLE 4 Radiation dosage stratified by high-risk procedure groups

	Era 1 (*n* = 18) Median [IQR]	Era 2 (*n* = 35) Median [IQR]	Era 3 (*n* = 12) Median [IQR]	*P* value
(A) Single ventricle diagnostic catheterizations with and without coiling of collaterals.				
Procedure types				.634
Pre–hemi Fontan	9	23	7	
Pre–Fontan	9	12	5	
Age (years)	1.6 [0.4-2.7]	1.0 [0.4-7.9]	1.7 [0.5-3.2]	.937
Weight (kg)	10. 2 [5.5-13.5]	7.8 [6.3-10.7]	10.6 [7.4-14.4]	.137
Fluoroscopy time (min)	24.2 [19.5-33.5]	24.6 [17.8-31.6]	25.2 [13.3-29.2]	.823
Contrast (mL/kg)	3.0 [2.5-3.6]	3.3 [2.8-3.8]	3.5 [2.2-3.9]	.641
Radiation dosage (µGym^2)	865 [471-1500]	579 [343-956]	342 [261-532]	.026
Radiation dosage (µGym^2/kg)	93.4 [65.2-134]	64.1 [52.0-103]	32.6 [22.6-47.7]	<.001
Radiation dosage (mGy)	176 [127-314]	119 [81-223]	54 [51- 120]	.001
	Era 1 (*n* = 18) Median [IQR]	**Era 2 (*n* = 26) Median [IQR]**	**Era 3 (*n* = 50) Median [IQR]**	***P* value**
(B) Complex interventions.				
Procedure types				.187
PA angioplasty/stent	11	18	32	
Conduit angioplasty/stent	2	1	11	
Melody valve implant	5	7	7	
Age (years)	11.9 [5.2-21.3]	11.7 [5.1-26.3]	8.8 [2.9-21.6]	.807
Weight (kg)	44.6 [18.3-70.3]	45.5 [17.6-58.9]	31.8 [15.7-57.6]	.670
Fluoroscopy time (min)	26.8 [20.1-37.8]	28.2 [17.4-41.1]	27.5 [18.3-38.5]	.290
Contrast (mL/kg)	2.6 [2.1-3.5]	2.7 [1.6-4.0]	2.8 [1.9-3.8]	.854
Radiation dosage (µGym^2)	7999 [1571-14413]	4303 [2334-9872]	1802 [1087-4533]	.004
Radiation dosage (µGym^2/kg)	182 [87.2-276]	135 [89.8-204]	70.8 [39.4-156]	<.001
Radiation dosage (mGy)	975 [371-2158]	715 [413-1222]	310 [13-773]	.001

increased from 15 to 30 f/s, 18 (78%) were for children ≤2 years and only 5 (22%) were diagnostic studies. This increase in frame rate was at the discretion of the interventional cardiologist performing the procedure. Our data suggest that higher frame rate may be required for better image quality for higher heart rates in younger patients and for interventional procedures (PDA device closure, pulmonary artery/conduit stent placement, balloon aortic valvuloplasty, balloon pulmonary valvuloplasty, etc).

We would like to mention that there are various ways in which radiation exposure to patients can be minimized in the catheterization lab. Few such techniques include: decreasing the acquisition times for fluoroscopy and cineangiography; decreasing the fluoroscopy and the cineangiography dose per frame and frame rate (as was done in our study); changing the camera angles (minimizing the left anterior oblique position); decreasing the distance between the x-ray tube and the patient; decreasing the magnification; reducing the size of the image by collimation; and finally using fluoroscopy only when needed.[17,18] The authors would like to encourage the

TABLE 5 Cineangiography image quality

Image quality	Cineangiography 30 f/s	Cineangiography 15 f/s	*P* value
Good to excellent	52	48	.155
Adequate	1	6	
Inadequate	1[a]	0	

[a]Neonate with pulmonary stenosis undergoing pulmonary valvuloplasty.

catheterization laboratory operators to use these techniques judiciously in order to decrease the overall radiation exposure to their patients.

5 | LIMITATIONS

This was a single-center retrospective study which may limit generalizability. As this study cohort included all the consecutive catheterization cases except electrophysiology studies using no fluoroscopic technique, selection bias was minimized. There were some differences in case mixture between eras. For example, in era 3, patients were older and weighed more. There were also a higher proportion of interventional procedures in era 3. Although there was a significant reduction in the median radiation dose per minute successively during the three eras, we were unable to calculate the radiation dose per frame. This was because in our quality improvement initiative, operators were allowed to increase the fluoroscopy pulse rate during the catheterization procedures at their discretion. Hence, it is possible that the observed radiation reduction could be due to the radiation dose optimization and/or improvement of operator technique during the study period. Patients with congenital heart disease have heterogeneous characteristics including underlying cardiac diagnosis, body size, and interventional procedures, making the comparison of the outcome measures challenging. We stratified cases by major procedural types and certain procedure groups, providing a valid comparison in each stratum. Also, trainees could affect the radiation dosage due to their educational time and tendency to use fluoroscopy longer; however, the distribution of trainee cases was similar between the eras. The total number of cineangiographies in each catheterization was not collected. The use of adjunct imaging technology (intraprocedural echocardiography and preprocedural cross-sectional imaging) and storing fluoroscopic imaging could influence the radiation dosage but were not collected in our study. Although our study focus was to evaluate the impact of pulse/frame rate on radiation dosage, we acknowledge that minimizing the duration of cineangiography and fluoroscopy use is always important. General awareness of radiation dosage is important and can reduce the radiation dosage. In our PCL, a quarterly review of the radiation dosage and fluoroscopy time was performed as a quality assurance activity and could influence our radiation safety practices.

6 | CONCLUSION

In our study, reduction of frame/pulse rate of both cineangiography and fluoroscopy successfully decreased the radiation dosage in the PCL. This was achieved without a compromise in procedural safety and diagnostic imaging integrity. This radiation reduction protocol is an important quality improvement in the PCL.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to disclose.

AUTHOR CONTRIBUTIONS

Shahnawaz M. Amdani and Daisuke Kobayashi were involved in the design, data collection and analysis, forming the initial draft of the manuscript, critical revisions, and in the approval of the final draft of the manuscript. Robert D. Ross, Daniel Turner, Thomas Forbes, and Paul Webster were involved in data collection, analysis, forming the initial draft of the manuscript, critical revisions, and the approval of the final draft of the manuscript.

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SUPPORTING INFORMATION

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

TABLE S1 List of cases where the frame rate of cineangiography was increased from 15 to 30 f/s during the procedure in the era 3

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