ORIGINAL ARTICLES

Cumulative Exposure to Medical Radiation for Children Requiring Surgery for Congenital Heart Disease

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Objective To describe cumulative radiation exposure in a large single-center cohort of children with congenital heart disease (CHD) and identify risk factors for greater exposure.

Study design A detailed medical radiation exposure history was collected retrospectively for patients aged <18 years who underwent surgery for CHD between January 1, 2001, and July 22, 2009. Cumulative per patient exposure was quantified as the effective dose in millisieverts (mSv) and annualized (mSv/year).

Results A total of 4132 patients were subjected to 134 715 radiation examinations at a median follow-up of 4.3 years (range, 0-8.6 years). Exposure clustered around the time of surgery. The median exposure was 14 radiologic tests (the majority of which were plain film radiographs) at an effective dose of 0.96 mSv (the majority of which was from cardiac catheterization), although this distribution had a very wide range. Almost three-quarters (73.7%) were exposed to <3 mSv/year, and 5.3% were exposed to >20 mSv/year. Neonates, children with genetic syndromes, and children requiring surgery for cardiomyopathy, pulmonary valve, single ventricle, or tricuspid valve diseases were more likely to have higher exposure levels, and those requiring surgery for aortic arch anomalies or atrioventricular septal defects were more likely to have lower levels.

Conclusion Children with CHD requiring surgery are exposed to numerous medical forms of ionizing radiation. Although the majority of patients receive <3 mSv/year, there are identifiable risk factors for higher exposure levels. This may have important health implications as these patients age. *(J Pediatr 2014;164:789-94)*.

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Congenital heart disease (CHD) is the most common birth defect, affecting nearly 1% of all live births. Many of these children will require surgical intervention at some point during childhood. Given the substantial improvement in short-term survival over the past few decades, more attention is now being paid to understanding and managing the longer-term complications. The use of ionizing radiation for both diagnostic and therapeutic procedures is a cornerstone of the management of children with CHD. Estimates of radiation exposure to children with CHD from single studies, such as cardiac catheterization, have been well characterized.[1-6] However, other than 2 small series,[7,8] the cumulative exposure burden from medical forms of ionizing radiation for children with CHD has not been studied. There is an increased lifetime risk of mortality from cancer with higher radiation exposure,[9-13] and this risk is likely higher when exposure occurs during childhood.[10,14,15] With an estimated 1.3 million people currently living with CHD in the US,[16] understanding the magnitude of radiation exposure during childhood is critically important. In this study, we examined the cumulative childhood radiation exposure for children with CHD needing cardiothoracic surgery and sought to define risk factors for increased exposure.

Methods

We performed a retrospective cohort study of all patients who underwent surgery for CHD at age <18 years at The Children's Hospital of Philadelphia (CHOP) between January 1, 2001, and July 22, 2009. Cases were excluded if the primary or secondary indication for the operation was not classified as a congenital heart defect. This study was approved by the Institutional Review Boards of the participating institutions, with waiver of the need for informed consent.

CHD	Congenital heart disease
CHOP	Children's Hospital of Philadelphia
CT	Computed tomography
mSv	Millisieverts

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The medical records of all included subjects were reviewed for date of birth, sex, race, date of operation, diagnoses made at the time of operation, operation type, and genetic syndrome or other chromosomal abnormality. Individual diagnoses were assigned to a diagnostic category based on anatomic features.

The cumulative exposure to medical forms of ionizing radiation was tallied from all studies performed at CHOP between birth and the end of follow-up for the inclusion cohort. Radiation exposure was quantified using the "effective dose," expressed in millisieverts (mSv), and reflects both the absorbed dose of radiation and the susceptibility of the exposed organ to the radiation-induced somatic or genetic effects. Examination-specific doses came from a comprehensive radiology look-up table devised by the Department of Radiology at CHOP (**Table I**; available at www.jpeds.com). The data used to populate the look-up table were derived through different examination-specific methodologies. Effective doses were calculated for radiographic and fluoroscopic studies using the Monte Carlo method with commercially available software (PCXMC version 2.0; STUK, Helsinki, Finland). Effective doses from computed tomography (CT) scans were calculated using the ImPACT CT Patient Dosimetry Calculator version 1.0 (St George's Hospital, London, England). Effective doses from nuclear medicine studies were estimated based on the conversion tables in International Commission on Radiologic Protection publications[17-19] for effective doses per unit of radioactivity administered with each radiopharmaceutical. The radioactivity administered per study was based on radiopharmaceutical administration reference charts used during the study period at CHOP.

Because the majority of catheterization procedures for this cohort were performed during a period when only total fluoroscopy time was recorded, we estimated effective dose in mSv using a 2-stage approach (**Table II**; available at www.jpeds.com), in a manner reported and validated previously.[20] First, linear regression was used to estimate the relationship between fluoroscopy time and measured dose-area product ($\mu Gy \cdot m^2$) in different weight categories, using available data from more recently studied patients for whom dose-area product was measured directly. Dose-area product was then converted to total effective dose (mSv) by the Monte Carlo method with commercially available software (PCXMC version 2.0), using conversion factors derived from age-specific phantom testing performed at CHOP that assumes that all radiation exposure comes from the posterior-anterior camera, as described previously.[21]

Descriptive statistics were used to summarize demographic, clinical, and radiation exposure data. All statistical analyses were performed in SAS version 9.2 (SAS Institute, Cary, North Carolina), and graphics were generated in R version 2.11.1 (http://cran.r-project.org/). Differences in the median number of examinations and radiation exposure by cardiopulmonary vs noncardiopulmonary examinations were tested using the paired sign-rank statistic. Radiation exposure for each patient was annualized as (cumulative exposure [mSv]/follow-up time [years]) and converted to an ordinal outcome variable based on the following "bins": <3 mSv/year (the average annual environmental background exposure for a person living in the US[22]), 3-20 mSv/year, and >20 mSv/year (the upper allowable occupational exposure for radiation workers as recommended by the International Commission on Radiologic Protection[12]).

Differences in annualized radiation exposure among age categories, sex, race, genetic syndromes, and diagnosis categories were calculated using the χ^2 test of independence or Fisher exact test. Polytomous logistic regression was used to identify associations among age categories, sex, race, genetic syndromes, and diagnosis categories and annualized radiation exposure categories in a multivariate model, with the <3 mSv/year category serving as the reference. The heterogeneity of effects for each predictor variable among radiation exposure categories was tested using polytomous logistic regression restricted to the 3-20 mSv/year and >20 mSv/year categories. Statistical significance was established at $P < .05$.

Results

A total of 4518 patients met the criteria for inclusion in the study. Data from 134 715 diagnostic and therapeutic radiation examinations were available for 4132 patients (91.5%), who constitute the cohort (**Table III**).

The range of number of radiologic examinations and effective doses across specific CHD diagnoses are summarized in **Figures 1** and **2** and **Tables IV** and **V** (**Figure 1** and **Tables IV** and **V** available at www.jpeds.com). For all except very rare diagnoses, the number of examinations and effective doses to which a patient was exposed ranged widely. Patients requiring surgery for a cardiomyopathy or single ventricle heart disease had the highest average number of total examinations. Although cardiac catheterizations represented a small fraction of the overall count, **Figure 2** shows that a disproportionately large share of the cumulative radiation exposure came from these procedures. Overall, patients requiring surgery for a cardiomyopathy, tricuspid valve disease, or pulmonary valve disease had the highest

Table III. Demographic characteristics of the cohort (n = 4132)

Characteristic	Value
Age at surgery, y, median (range)	0.3 (0-18.0)
Age category at surgery, n (%)	
Neonate (0-30 d)	1481 (35.8)
Infant (31 d-1 y)	1252 (30.3)
Child (1-18 y)	1399 (33.9)
Male sex, n (%)	2258 (54.6)
Identified genetic syndrome, n (%)	603 (14.6)
Race, n (%)*	
White	1681 (62.0)
Black/African American	519 (19.2)
Asian	37 (1.4)
Other	473 (17.4)
Age at first radiation exposure, y, median (range)	0.5 (0-22.3)
Follow-up from first radiation exposure, y, median (range)	4.3 (0-8.6)

*Data on race are missing for 34% of the cohort.