Lifetime Prevalence of Congenital Heart Disease in the General Population From 2000 to 2010

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Background—Our objective was to obtain contemporary lifetime estimates of congenital heart disease (CHD) prevalence using population-based data sources up to year 2010.

Methods and Results—The Quebec CHD database contains 28 years of longitudinal data on all individuals with CHD from 1983 to 2010. Severe CHD was defined as tetralogy of Fallot, truncus arteriosus, transposition complexes, endocardial cushion defects, and univentricular hearts. We used latent class bayesian models combining case definitions from physician claims, hospitalization, and surgical data to obtain point and interval prevalence estimates of CHD in the first year of life, in children (<18 years of age) and in adults. We identified 107 559 CHD patients from 1983 to 2010. Prevalence of CHD in the first year of life was 8.21 per 1000 live births (95% confidence interval, 7.47–9.02) from 1998 to 2005. In 2010, overall prevalence of CHD was 13.11 per 1000 (95% confidence interval, 12.43–13.81) in children and 6.12 per 1000 (95% confidence interval, 5.69–6.57) in adults. CHD prevalence increased by 11% in children and 57% in adults from 2000 to 2010. Prevalence in the severe CHD subgroup increased by 19% (95% confidence interval, 17%–21%) in children and 55% (51%–62%) in adults. By 2010, adults accounted for 66% of the entire CHD population.

Conclusions—With an increase of >50% in CHD prevalence since 2000, by 2010 adults accounted for two thirds of patients with severe and other forms of CHD in the general population. Our findings should inform allocation of resources and the planning of workforce needs for the predominantly adult CHD population. **(*Circulation*. 2014;130:749-756.)**

Key Words: epidemiology ■ health services ■ heart defects, congenital ■ prevalence

Congenital heart disease (CHD) is diagnosed in 8.14 of 1000 or close to 1% of births in the United States.[1] Advances in medical and surgical therapy have increased the survival of CHD patients.[2–6] It is now recognized that CHD is associated with lifelong comorbidity that impacts health services utilization and costs. The impact of ongoing disease burden includes atrial arrhythmias,[7] pulmonary hypertension,[8] and a repeated need for surgery,[9] which results in significant increases in health services utilization during childhood,[10] transition years,[11] adulthood,[12] and in the geriatric age group.[13] Not surprisingly, in the United States in 2004, birth defects accounted for >139 000 hospitalizations, of which 46 500 were for cardiac and circulatory anomalies. In the same year, whereas hospital costs associated with all birth defects totaled $2.6 billion, an approximate $1.4 billion was directly attributable to cardiovascular anomalies.[14] Therefore, although cardiovascular birth defects accounted for only 34% percent of stays for birth defect hospitalizations, they constituted more than half the costs. Thus, as the demographic distribution of disease changes, policy makers need accurate estimates of the growing numbers of CHD patients.

Clinical Perspective on p 756

Using administrative databases with universal health coverage, in Quebec, Canada, first-time estimates of time trends from 1985 to 2000 in the CHD prevalence in the general population were published.[3] A 22% increase in children and 85% increase in adults with severe CHD was documented from 1985 to year 2000, with the number of adults accounting for just over 50% of the total CHD population by the year 2000.[3,15]

Our goal in the present study was to provide contemporary population-based estimates for CHD prevalence across the life-span. Our specific objectives were to estimate the lifetime prevalence of CHD; to compare the number of adults to the number of children with CHD in the Quebec population from 2000 to 2010; and to estimate the change in prevalence of severe CHD in Quebec from 2000 to 2010 in adults compared with children. We also sought to determine the prevalence of CHD in infants. In addition to doing so for the year 2010, to be consistent with the study period of the Centers for Disease Control and Prevention (CDC) in Atlanta, GA, we estimated

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the prevalence of CHD in the first year of life from 1998 to 2005.[1]

Methods

Data Sources

In Quebec, Canada, every individual is assigned a unique Medicare number in the first year of life that is used to track all diagnoses and health services rendered and systematically recorded until death. Administrative databases include the physicians' services and drug claims, hospital discharge summary databases, and the Quebec Health Insurance Board and Death Registry.[3] These contain demographic and vital statistics data, as well as all *International Classification of Diseases, 9th Revision* (*ICD-9*) and *10th Revision* (*ICD-10*; as of 2006) diagnostic codes and procedure codes recorded with or without a hospitalization in Quebec since 1983.

To create the Quebec Congenital Heart Disease Database from 1983 to 2000, information on all patients with a CHD diagnosis from any of the 3 data sources were merged and cleaned onsite at the McGill Adult Unit for Congenital Heart Disease Excellence. Patients were identified with CHD if they had at least 1 diagnostic code for CHD or a CHD-specific surgical procedure, and diagnostic algorithms were developed as published to optimize the extraction of valid CHD diagnoses.[3] To increase the specificity of the algorithms, manual audits were performed independently by an adult congenital heart disease specialist (A.J.M.) and a pediatric cardiologist (A.S.M.) on the original data set from 1983 to 2000, which consisted of 61 386 subjects. These were performed on random samples of 19 073 (or 31%) of included and excluded subjects in the raw data set to adjudicate discrepant diagnoses and adjust algorithms accordingly.[3]

Data Collection

For the present study, using the same patient-encrypted unique identifiers used for the data from 1983 to 2000, data updates were requested from the same and only administrative data source in Quebec up to the year 2010. Because a subject carries a diagnosis of CHD since birth, each subject entered each birth cohort based on his or her age, regardless of the calendar year of diagnosis. To minimize misclassification and increase the sensitivity of using CHD diagnostic codes to capture CHD patients, we used all available data for a given subject over a 28-year observation period, including inpatient, outpatient, procedural, and provider information. This was done by cross-referencing all available province-wide administrative databases. Patients who had >15 years of observation with only a single contact with the healthcare system billed as a severe or unspecified CHD diagnosis were excluded. New data were thus obtained on existing and new CHD cases diagnosed from 1983 to 2010 on a total of 157 395 subjects (Figure 1), to whom we applied our previously published algorithms[3] to arrive at the total number of subjects with a CHD diagnosis in Quebec by the year 2010. All data used in the present study were deidentified, and the study was approved by the Quebec Commission for Access to Information, which regulates access to confidential data in Quebec.

The updated Quebec CHD database therefore contains comprehensive longitudinal, demographic, diagnostic, and therapeutic records of all patient-linked encounters with the healthcare system from January 1, 1983, to December 31, 2010 (inclusive) for all Quebec residents identified with CHD linked with a singular scrambled identifier over a patient's life. Severe CHD was defined as tetralogy of Fallot, truncus arteriosus, transposition complex, endocardial cushion defects, univentricular heart, and hypoplastic left heart syndrome, as published previously.[3] All remaining diagnoses were considered "other" CHD lesions. The prevalence analysis in 2010 consisted of the number of patients who were alive with CHD in Quebec as of midyear 2010 (numerator) and the midyear 2010 Quebec general population (denominator), which was 7 929 365, comprising 1 523 722 children and 6 405 643 adults.[16] For the prevalence analysis in 2005, the Quebec population in mid-2005 consisted of 1 550 513 children and 6 030 679 adults.[16] For the prevalence estimate in infants, the total number of infants alive with CHD was measured at midyear of each year from 1998 to 2005 and divided by 589 570, or the total number of infants alive in the Quebec population during the same years.[16] These dates were chosen to overlap with the observation period of data from the CDC. The same analysis was also performed for 2010 with 87 760 as the denominator for the Quebec infant population.[16] Age in a specific year was defined as the age, in years, as of July 1st of that year. Infants were defined as aged <1 year, children as aged <18 years, and adults ≥18 years of age, respectively.

Statistical Analysis

Prevalence during a specific year was defined as the number of case subjects who were alive as of July 1st of that specific year and who

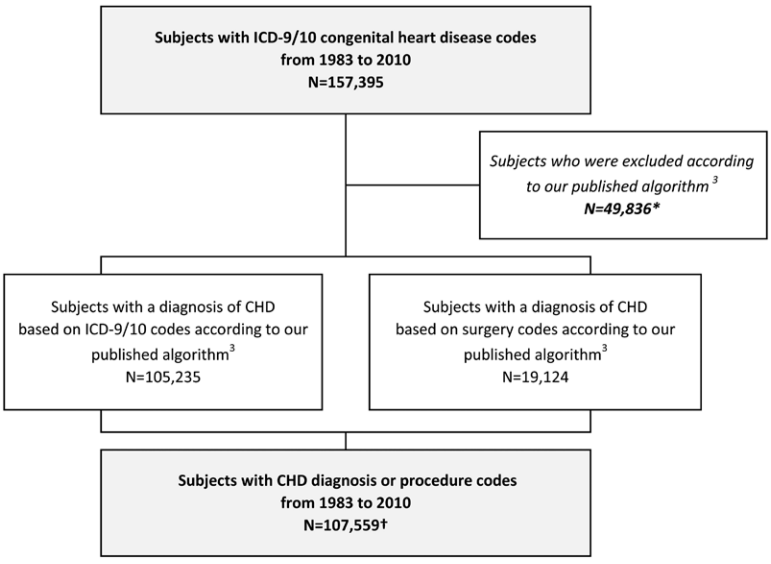

Figure 1. Identification of subjects with a congenital heart disease (CHD) diagnosis in 6 405 643 adults and 1 523 722 children in Quebec, Canada, from 1983 to 2010. *A total of 49 836 subjects were excluded in accordance with previously published algorithms.[3] This included subjects never hospitalized for CHD and without CHD-specific surgery and with no CHD diagnosis made by a cardiovascular specialist; those whose CHD diagnoses were not made by a cardiovascular specialist or a primary care physician or echocardiographer; and those whose CHD-specific surgical procedure was billed by a noncardiovascular surgical specialist, without an *International Classification of Diseases, 9th Revision* or *10th Revision* (*ICD-9/10*) CHD diagnosis. Patients who had >15 years of observation with only a single contact with the healthcare system billed as a severe or unspecified CHD diagnosis were excluded. †The subgroup with *ICD-9/10* diagnoses for CHD (n=105 235) and the subgroup with CHD surgery codes (n=19 124) are not mutually exclusive: 16 800 subjects had both *ICD-9/10* and surgery codes for CHD. The sum of the patients with *ICD-9/10* diagnosis of CHD and those with a CHD diagnosis based on surgical codes minus those who had both constitutes the number of patients with a final CHD diagnosis in Quebec between 1983 and 2010.

were diagnosed before the end of that specific year, divided by the size of the corresponding midyear Quebec population. Prevalence was reported as the number of cases per 1000 individuals. The prevalence ratio of 2 different calendar years corresponded to the ratio of their corresponding prevalence estimates. The proportion of adults and children with CHD was defined as the number of adults and children divided by the total number of CHD patients alive in that year.

We obtained data on 61 386 subjects from 1983 to 2000 and new data on a total of 157 395 subjects by the year 2010. We determined that we could not reasonably perform manual audits on the new data by readjusting our algorithms based on the longer observation period. Because there is no perfect measure of CHD prevalence, we used bayesian latent class models to account for uncertainty around the point estimates.[17] The *ICD-9* codes and the surgical procedure codes are both imperfect measures of the underlying true CHD status, which is latent. Adopting the terminology used for evaluation of diagnostic tests, we describe the *ICD-9* codes as having high sensitivity and low specificity, whereas the surgical procedure codes had high specificity but low sensitivity. Separate latent class models were used to predict prevalence of different types of lesions, as well as "all lesions," "severe lesions," and all "other lesions." This type of model has been used for the estimation of disease prevalence in the absence of a "gold standard" test,[17] and similar models have been applied to estimate the prevalence of various outcomes using imperfect measures from administrative databases.[18–20]

To obtain a meaningful estimate of prevalence, some information external to the data (referred to as prior information) must be provided on at least 2 parameters.[17] To ensure that prior data would not be used twice to derive prior distribution and the likelihood, we used the sensitivity of procedure codes estimated with data over the first 14 years of the follow-up period (1983–1996) to elicit a prior distribution for the sensitivity of procedure codes over a second 14-year period (1996–2010), such that the 2 periods did not overlap. The 95% confidence interval (CI) for the sensitivity estimate obtained from the earlier cohort (data from January 1, 1983, to December 31, 1996) was used to define the lower and upper bounds of the prior distribution. On the basis of our previous work using the Quebec CHD database from 1983 to 2000,[3] as described above, our prior knowledge of the CHD-specific surgical procedure codes suggests the specificity is as close to 100% as possible.

Each individual in the midyear Quebec population of 2010 was thus assigned to 1 of 4 cells of a 2×2 table on the basis of the results of diagnoses of CHD by the 2 ascertainment methods. Likelihood was then constructed based on the multinomial distribution of the 4 categories in the 2×2 table. The unknown parameters in the model are the CHD prevalence (our primary parameter of interest) and the sensitivity and specificity of the 2 imperfect measures.

The same methodology was used to obtain prevalence rates for adults and children in 2005 and for infants in the first year of life from 1998 to 2005. The prevalence of severe CHD was estimated in a similar way but with the *ICD-9* codes for severe CHD in the numerator as defined above and as published previously.[3] Age-specific prevalence was estimated with the prior data obtained from the corresponding age categories.

All descriptive analyses were performed with SAS software (SAS/STAT software version 9.2, SAS Institute, Inc, Cary, NC). Estimations of the latent class models, such as prevalence and its 95% credible interval, were computed with WinBUGS software version 1.4.3.[21] Details on the variables used for the latent class models and technical details on the programs used are described in the Appendix in the online-only Data Supplement.

Results

Figure 1 illustrates the derivation of the 107 559 subjects in the Quebec health claims databases who had either a CHD diagnosis or a congenital cardiac procedure code from 1983 to 2010. After application of our algorithms and the latent class modeling to account for uncertainty about the true CHD status or prevalence of CHD, it was estimated that 39 051 adults and 20 011 children with CHD were alive in midyear 2010 in Quebec (95% CIs, 36 307–41 922 and 18 973–21 079, respectively), as shown in the Table.

Lifetime Prevalence of CHD

The prevalence of CHD across age groups is presented in Figure 2. A prevalence of 13.11 (95% CI, 12.43–13.81) per 1000 children and 6.12 (95% CI, 5.69–6.57) per 1000 adults was documented in 2010. A subgroup analysis was performed in children to identify the birth prevalence in the first year of life from 1998 to 2005 and in 2010. We obtained a rate of 8.21 (95% CI, 7.47–9.02) for years 1998 to 2005 and 8.12 (95% CI, 7.59–8.87) per 1000 infants for 2010.

Prevalence by lesion for 2010 is summarized in the Table. The prevalence of severe CHD was 1.76 (95% CI, 1.68–1.84) per 1000 children and 0.62 (95% CI, 0.56–0.68) per 1000 adults. Conotruncal anomalies (tetralogy of Fallot, truncus arteriosus, transposition complex) were present at a rate of 0.98 per 1000 children and 0.33 per 1000 adults. The prevalence of other CHD was 11.34 (95% CI, 10.67–12.04) per 1000 children and 5.50 (95% CI, 5.07–5.95) per 1000 adults. All shunt lesions, including unspecified defects of septal closure, had prevalence values of 9.19 per 1000 children and 1.60 per 1000 adults. Valve lesions, including congenital aortic stenosis or insufficiency, anomalies of the pulmonary artery or valve, congenital mitral or tricuspid valve disease, and Ebstein's anomaly, had a prevalence of 1.28 per 1000 children and 1.73 per 1000 adults.

Change in Proportion of Adults and Children in Years 2000, 2005, and 2010

The number of adults and children with any CHD is presented in Figure 3. For children, the number (95% CI) with any CHD remained relatively stable, with 18 913 (18 586–19 241) in 2000 and 20 011 (18 973–21 079) in 2010. For adults however, the number (95% CI) with any CHD went from 22 291 (19 181–25 402) in 2000 to 39 051 (36 307–41 922) in 2010 (Figure 3A). Similarly, although the number of children with a severe lesion increased slightly from 2355 (95% CI, 2283–2427) in 2000 to 2686 (95% CI, 2564–2809) in 2010, a substantial increase was observed in the number of adults with severe CHD, which went from 2275 (95% CI, 2131–2419) in 2000 to 3956 (3573–4339) in 2010 (Figure 3B).

The proportion of subjects with CHD who were adults increased from 54% (95% CI, 51%–57%) in 2000 to 66% (95% CI, 64%–68%; Figure 3A). Similarly, in 2010, adults represented 60% (95% CI, 57%–62%) of all subjects with severe CHD compared with 49% (95% CI, 47%–51%) in 2000 (Figure 3B).

Changing Prevalence in Adults and Children in Years 2000, 2005, and 2010

From 2000 to 2010, we noted an increase in the prevalence of all CHD and severe CHD in both children and adults; however, a much larger increase was observed in adults than in children. The prevalence of CHD increased by 57% (95% CI, 48%–71%) in adults compared with 11% (95% CI, 5%–17%) in children, and as a consequence, adults represented two thirds of the CHD population in 2010. Similarly, an increase in the

Table. Prevalence of Severe and Other Congenital Heart Disease in Quebec, Canada, in the Year 2010

	Children Alive in 2010 in Quebec		Adults Alive in 2010 in Quebec	
	n (95% CI)	Prevalence per 1000 (95% CI)	n (95% CI)	Prevalence per 1000 (95% CI)
All congenital heart lesions	20 011 (18 973–21 079)	13.11 (12.43–13.81)	39 051 (36 307–41 922)	6.12 (5.69–6.57)
Severe lesions				
Tetralogy of Fallot or truncus arteriosus	901 (863–939)	0.59 (0.57–0.61)	1467 (1342–1592)	0.23 (0.21–0.25)
Transposition complex	595 (580–626)	0.39 (0.38–0.41)	638 (574–702)	0.10 (0.09–0.11)
Endocardial cushion defect	809 (763–840)	0.53 (0.50–0.55)	1340 (1212–1468)	0.21 (0.19–0.23)
Univentricular heart	229 (214–229)	0.15 (0.14–0.15)	319 (255–319)	0.05 (0.04–0.05)
Hypoplastic left heart syndrome	137 (137–153)	0.09 (0.09–0.10)	191 (191–191)	0.03 (0.03–0.03)
All severe lesions	2686 (2564–2809)	1.76 (1.68–1.84)	3956 (3573–4339)	0.62 (0.56–0.68)
Other lesions				
Atrial septal defect	7464 (7006–7953)	4.89 (4.59–5.21)	5424 (5169–5743)	0.85 (0.81–0.90)
Ventricular septal defect	5114 (4793–5449)	3.35 (3.14–3.57)	3956 (3765–4148)	0.62 (0.59–0.65)
Patent ductus arteriosus	1328 (1252–1420)	0.87 (0.82–0.93)	510 (510–574)	0.08 (0.08–0.09)
Unspecified defect of septal closure	122 (107–122)	0.08 (0.07–0.08)	319 (319–319)	0.05 (0.05–0.05)
Aortic coarctation	412 (397–443)	0.27 (0.26–0.29)	574 (574–574)	0.09 (0.09–0.09)
Congenital aortic stenosis or insufficiency	748 (382–1114)	0.49 (0.25–0.73)	6253 (5551–7019)	0.98 (0.87–1.10)
Anomalies of the pulmonary artery or valve	992 (654–1330)	0.65 (0.43–0.87)	2042 (1874–2210)	0.320 (0.29–0.35)
Congenital mitral or tricuspid valve disease	183 (92–275)	0.12 (0.06–0.18)	2552 (2297–2871)	0.40 (0.36–0.45)
Ebstein's anomaly	31 (15–46)	0.02 (0.01–0.03)	191 (191–255)	0.03 (0.03–0.04)
Anomalies of great veins	15 (15–31)	0.01 (0.01–0.02)	255 (255–319)	0.04 (0.04–0.05)
Unspecified congenital anomalies	870 (443–1282)	0.57 (0.29–0.84)	13 655 (12 188–15 314)	2.14 (1.91–2.40)
Unknown congenital heart lesions	15 (15–31)	0.01 (0.01–0.02)	702 (638–830)	0.11 (0.10–0.13)
All other lesions	17 325 (16 287–18 378)	11.34 (10.67–12.04)	35 095 (32 351–37 967)	5.50 (5.07–5.95)

CI indicates credible interval.

prevalence of severe lesions of 55% (95% CI, 51%–62%) was estimated in adults, which is larger than the 19% (95% CI, 17%–21%) increase estimated in children (Figure 4).

Prevalence Ratios of CHD Population Stratified by Age in Year 2010 Compared With Year 2000

We analyzed how the increase in prevalence ratios of all lesions and severe lesions behaved within specific age categories, as presented in Figure 5A and 5B. Prevalence ratios for 2010/2000 indicate that in those with severe disease, the largest increase was observed among those aged ≥26 years, with a prevalence ratio of 1.84 (95% CI, 1.67–2.03) in those 26 to 40 years of age and 1.79 (95% CI, 1.68–1.89) among those aged ≥41 years. Prevalence ratios for total CHD followed the same trends, with the largest increase observed in adults >26 years of age, although the rise was not as sharp in young adults 18 to 25 years of age.

Discussion

This study is unique in providing contemporary population-based estimates of the lifetime prevalence of CHD based on longitudinal follow-up. In 2010, adults represented 66% of the total number of people alive with CHD in Quebec who had severe and other forms of CHD. Therefore, adults with CHD now constitute a significant majority of CHD patients accessing the healthcare system in the general population, which compels us to reshape the delivery of healthcare services for patients with CHD. From 2000 to 2010, the prevalence of severe CHD rose at faster rates for adults than for children, consistent with ongoing improvement in care and survival. In the Quebec CHD database, as presented in the present study, we observed a prevalence of CHD in infancy that was remarkably close to the most commonly reported rate of birth prevalence of CHD in the United States.[1] This finding supports the use of our data to estimate the number of adults with CHD in the United States and underscores the fact that population-based empirical measurements can and should be sought in other jurisdictions.

From 2000 to 2010, the increase in prevalence of severe CHD in adults was 55% (95% CI, 51%–62%), compared with an 85% increase previously observed from 1985 to 2000.[3] Despite a slower rate of rise, adults with CHD now constitute 60% of the severe CHD population and 66% of people with other CHD. Consistent with this observation, the largest increase in prevalence stratified by age occurred for those 18 to 40 years of age from 2000 to 2010 compared with those in the 13- to 17-year-old age range from 1985 to 2000. As a result of this larger increase in adults than in children, the median age of people alive with severe CHD in the Quebec population increased by 14 years from 1985 to 2010. The median age was estimated in a previous publication by Marelli et al[3] to be 11 years in 1985 and 17 years in 2000, whereas in the present study, we found that the median age of people with severe CHD in 2010 was 25 years in 2010. The sequential increase in

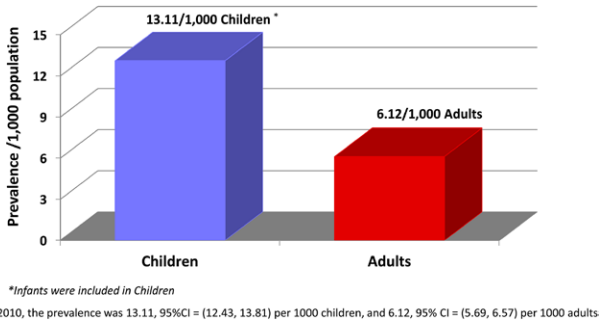

Figure 2. The lifetime prevalence of congenital heart disease in children and adults in Quebec, Canada, in 2010. 95%CI indicates 95% credible interval.

age of the most rapidly growing segment of the CHD population suggests that the next decades will witness an increasingly older population of patients with not only severe CHD but comorbidity that is expected to add to the disease burden.[13]

Improved care, decreased mortality, and improved diagnosis over the life-span are likely contributors to the observation of an increasing prevalence of CHD. We and others have found a decrease in mortality of CHD patients, as documented in Canada, the United States, and other industrialized nations.[4,6,22] This decrease in mortality over time is likely an important contributing factor to an increasing pool of patients with prevalent CHD, especially for patients with severe CHD. For patients with mild forms of CHD, such as aortic and mitral valve disease, the rise in prevalence from childhood to adulthood is consistent with improvement in diagnostic techniques and presentation in adulthood, with an increased likelihood of being captured with longer observation periods. For example, bicuspid aortic valve is often not detected in childhood because the physical finding (a click) is subtle, and until stenosis or regurgitation develops, often not until adulthood, the diagnosis is not made. The reported rise in adults of mitral or tricuspid valve disease could be attributable to progressive atrioventricular valve regurgitation after endocardial cushion defect repair. Recently, we have observed a significant decrease in mortality associated with the delivery of specialized care for adults with severe and other forms of CHD.[23] These findings taken together provide the evidence base needed to improve quality of care for adults with CHD[24] to improve outcomes.

In the Quebec CHD database, we observed a prevalence of CHD in infancy of 8.21 per 1000 from 1998 to 2005 and 8.12 per 1000 for the year 2010. Our results show that the 2010 CHD prevalence in infancy was lower than the prevalence in childhood. The most likely explanation for this is related to ascertainment of mild CHD, which is often diagnosed later in childhood. Therefore, it is not surprising that with up to 18 years of follow-up in children, we captured higher rates of total CHD prevalence, which included both

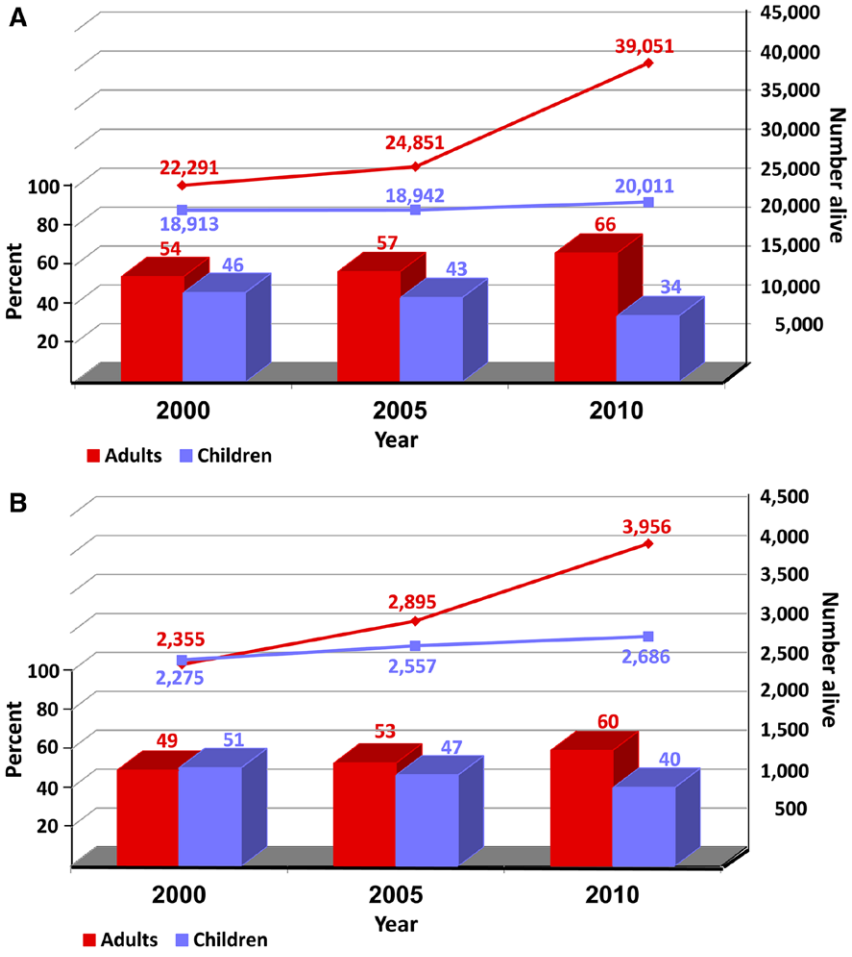

Figure 3. The numbers and proportions of adults and children in Quebec, Canada, with all (**A**) and severe (**B**) congenital heart disease over time in 2000, 2005, and 2010.

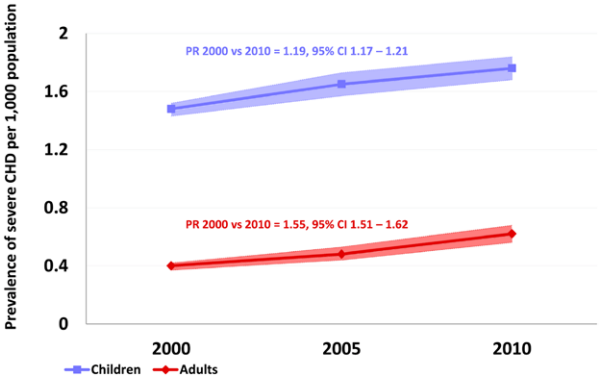

Figure 4. Change in congenital heart disease prevalence of children and adults in Quebec, Canada, from 2000, 2005, and 2010 for patients with severe congenital heart disease. CHD indicates congenital heart disease; CI, credible interval; and PR, prevalence ratio.

severe and milder forms of CHD. The analysis from 1998 to 2005 was performed for comparative purposes with other analyses of birth prevalence. Although our methodology is different from that of Reller et al,[1] our findings are within the same range as the rate of 8.14 per 1000 published by the CDC in the United States[1] and similar to the most commonly reported rate of birth prevalence of CHD in industrialized nations, which clusters around 8 per 1000.[25] Midyear was used for infants because Statistics Canada, from which the denominators were taken, reports population estimates at July 1 of each year.[16] This insured that the same inclusion criteria were applied to the numerator and denominator of prevalence rate estimates in infants. To the extent that infant mortality is low in the current era, the midyear population of infants can be expected to be a reasonable proxy for the (live) births in a given year. The similarity in birth prevalence rates between the present data and the US data lends credibility to the extrapolation of our findings to jurisdictions where advances in medical and surgical therapy are expected to yield similar results in survival.[4]

Population-based prevalence rates may be extrapolated to arrive at estimates of the number of people alive with CHD. The challenge in measuring prevalence in children and adults is in obtaining a meaningful denominator. Because of universal health coverage in Canada and the use of a unique identifier throughout a subject's life, the Quebec CHD database is one of the only data sources available that relates prevalence measurements to a comprehensive population denominator. Extrapolating the findings of the present study to an approximately 34 million people,[16] we estimate that there are a total of 257 138 people alive with CHD in Canada. Indexed to the population by age,[16] we expect that in 2010, there were 166 428 and 90 710 adults and children with CHD, respectively, in Canada. This constitutes a sharp increase compared with our 2000 findings, at which time there were 96 324 adults and 84 868 children with CHD for a Canadian population of approximately 31 million inhabitants,[15] reflecting a near 70% increase in the number of adults alive with CHD. The predominantly adult CHD patient population has now been documented to fall squarely within the jurisdiction of adult healthcare providers.

In the United States, the 32nd Bethesda Conference estimated that in year 2000, the total number of adults living with CHD in the United States was 800 000.[26] Consistent with these numbers, Canadian data extrapolated to the United States for the year 2000 estimated that for a country population of approximately 281 million, there were 855 334 adults and 859 573 children with CHD.[15] Although there are no available published estimates for prevalence rates of CHD beyond birth for 2010 for comparative purposes in the United States, the present data are in line with the expected increase in the CHD population over time.[2] The present findings suggest the adult population of CHD patients in the United States is approximately 1.5 million, which underscores the need for data supporting more robust US-based population estimates.

The present study should be interpreted in light of the study design. To minimize misclassification bias arising from the use of administrative databases,[27] we maximized the accuracy of CHD diagnosis by developing algorithms that cross-referenced diagnoses and procedures from multiple sources (described previously) and by validation through a systematic manual review process applied to randomly chosen samples of 31% of the original 1983 to 2000 group of patients.[3] Even so, some degree of misclassification may be present, particularly with milder forms of CHD, such as mitral valve anomalies diagnosed in adulthood. To optimize generalizability, we used the entire population of Quebec, Canada's second-largest province, as our study population, and we compared CHD prevalence in infants and adults from the present study with those published in the United States. CHD birth prevalence in the present study was in line with

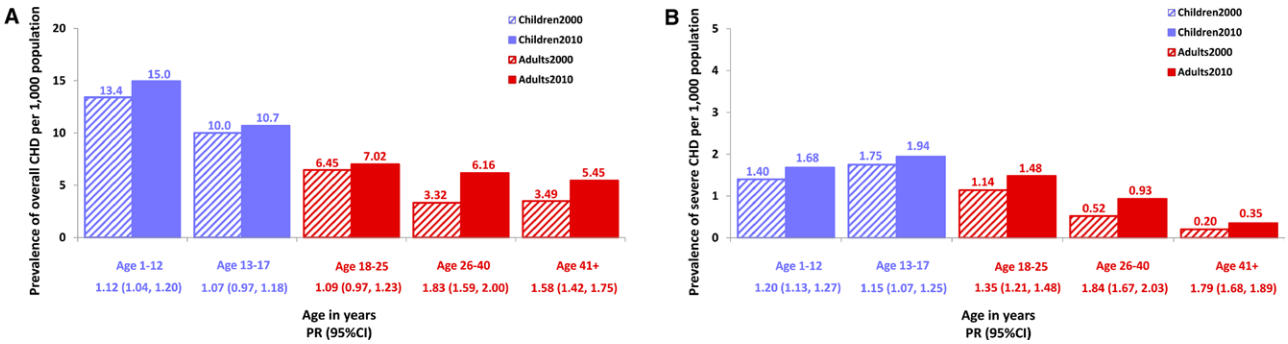

Figure 5. Change in prevalence ratios of congenital heart disease in Quebec, Canada, from 2000 to 2010 for all (**A**) and severe (**B**) CHD stratified by age. CHD indicates congenital heart disease; CI, credible interval; and PR, prevalence ratio.

estimates of CHD birth prevalence in the United States.[1] Although our methodology differed from that of the CDC in that we did not include stillborn infants and our data collection methods differed, the fact that the reported rate in Quebec is similar to CDC rates in the United States is reassuring. To minimize ascertainment bias arising from longer observation periods using administrative data sources, we used bayesian latent class methodology, which accounts for uncertainty in the data about the true CHD status of a subject. This is particularly important for milder forms of CHD, for which detection can increase with enhanced imaging even in the absence of symptoms over the course of a lifetime. In contrast, all severe forms of CHD had prevalence rates that were lower in adults than in children. We reported a prevalence of severe CHD in children of 1.7 per 1000. This is not dissimilar to the prevalence of CHD requiring cardiac catheterization in the first year of life of 1.5 per 1000 reported by Fyler[28] more than 3 decades ago. This reassures us that detection of severe disease in children is robust and illustrates the spectrum of factors that complicate empirical measurement of CHD across a patient's life. These include disease severity, ascertainment technique, age at diagnosis, and cohort effect. Thus, in the present analysis, we have applied a methodology that highlights the difference between "CHD diagnosis" as can be measured empirically in large population-based data sources and "CHD prevalence," which is our best estimate of true disease status. Misinformation bias may occur because of migration rates; emigration and immigration could lead to overestimation or underestimation of prevalence rates, respectively, by modifying the denominator. However, the Quebec population is relatively stable. In 2010, there was a net migration into the province of 44 215 people in a population of 7.9 million people,[29] which results in a possible error of 0.6% in our prevalence estimate. This would account for misclassification of a maximum of 645 of the 107 559 subjects with CHD diagnosis codes (Figure 1). Finally, the accuracy of our prevalence estimates depends on the extent to which the source population for the Quebec health system reflects the total Quebec population. Although Quebecers may theoretically seek care outside the province, there are few incentives for doing so, because this would involve out-of-pocket costs for services that are covered by universal health insurance in Quebec. Furthermore, even if some patients did elect to pay for procedures performed outside Quebec, subjects would still be captured in our database if they had any healthcare encounter in Quebec with a CHD diagnosis at any time during our long observation period.

Notwithstanding these limitations, this is one of the only data sources available that enables contemporary estimates for the number of people alive with CHD across the life-span in the general population. By 2010, adults accounted for nearly two thirds of patients with severe and other forms of CHD. These findings highlight an emerging public health issue. There is no longer any doubt that the care of well over half of the CHD population falls squarely in the arena of adult medicine. The present study is expected to inform policy makers both in terms of the organization of health services delivery and workforce allocation to meet the needs of this population, whose demographics have changed. The present findings underscore the need for longitudinal data sources in the United States that will enable more granular calculations of the CHD population across the life-span and more contemporary population-based estimates in jurisdictions where such data can be made available.

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CLINICAL PERSPECTIVE

This study is unique in providing contemporary population-based estimates of the lifetime prevalence of congenital heart disease (CHD) based on longitudinal follow-up. Using administrative databases with universal health coverage, in Quebec, Canada, first-time estimates of time trends from 1985 to 2000 of CHD prevalence in the general population were published. We showed that the number of adults accounted for just over 50% of the total CHD population by the year 2000. In this study, we provide updated data to 2010, by which time adults represented 66% of the total number of people alive with CHD in Quebec with severe and other forms of CHD. From 2000 to 2010, the prevalence of severe CHD rose at faster rates for adults than for children, consistent with ongoing improvement in adult care and survival. In the Quebec CHD database, as presented in this study, we observed a prevalence of CHD in infancy similar to the most commonly reported rate of birth prevalence of CHD in the United States and other industrialized countries. This finding supports the use of our data to estimate the number of adults with CHD in the United States. Adults with CHD now constitute a significant majority of CHD patients accessing the healthcare system in the general population. Care of the CHD population now falls squarely in the arena of adult medicine. Our study is expected to inform policy makers in reshaping the delivery of healthcare services in a population whose demographics have changed. These findings highlight an emerging public health issue and underscore the need for population-based empirical measurements in other jurisdictions.

Lifetime Prevalence of Congenital Heart Disease in the General Population From 2000 to 2010

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SUPPLEMENTAL MATERIAL

Statistical Appendix

A.1 Derivation of prior distributions

Based on our previous work we reasonably assumed that misclassification errors had been minimized in the CHD database up to the year 2000 since this data had been validated through manual audits independently adjudicated by 2 CHD experts. This was performed on 17,474 of the original 61,386 subjects in the original data over the course of 3 years with adjustment of the algorithms after each set of manual audits as previously published.[3] We therefore sought a statistical method that would allow us to incorporate reasonable uncertainty around our estimates of CHD prevalence using validated prior information. Hence our choice of Bayesian methodology[17] as rationalized in the Statistical Methods section of the manuscript.

Data over the first 14 years of follow up (from January 1, 1983 to December 31, 1996) was thus used to obtain an estimate of the sensitivity of procedure codes. This sensitivity was obtained as the number of patients alive as of midyear 1996 and who had a procedure code from January 1, 1983 to December 31, 1996 divided by the total number of patients alive as of midyear 1996 and who were in our CHD database. The 95% confidence interval for the sensitivity estimate obtained from the above-stated period was used to define the lower and upper bounds of the prior distribution for the sensitivity of procedure codes.

Our prior knowledge of the surgical procedure codes suggests the specificity was as close to 100% as possible.

For the remaining three parameters (sensitivity and specificity for the ICD-9 code and the prevalence), we used non-informative uniform prior distributions on the interval (0, 1), which means that *a priori* these parameters can take any value between 0 and 1.

A. 2 Likelihood contributions for latent class models

The cross tabulation of the results of the ICD-9 code and the surgical procedure code can be presented in a 2x2 table as described in Table A.1.

Table A1

No of subjects (probability)		Surgical code +	Surgical code -
ICD-9 code	+	Y1 (p1)	Y2 (p2)
	-	Y3 (p3)	Y4 (p4)

p1+p2+p3+p4=1

The likelihood based on the 2x2 table is then given by the multinomial distribution with cell probabilities p1, p2, p3 and p4.

Since there is no perfect measure of CHD prevalence, a latent class model is constructed. For a given latent class model, we denote by π the prevalence, by S_1 and C_1 the sensitivity and specificity, respectively, of the ICD-9 code, by S_2 and C_2 the sensitivity and specificity, respectively, of the surgical code for that latent variable. The likelihood contributions for a given latent class model are listed in the table below**.** In each line of the table we have the probability

of all possible combinations of observed and latent data for 2 methods of ascertainment**.**

Table A2

No. of subjects	True CHD status	ICD-9 code	Surgical code	Likelihood contribution
X1	+	+	+	$\pi S_1 S_2$
X2	+	+	-	$\pi S_1(1-S_2)$
X3	+	-	+	$\pi(1-S_1)S_2$
X4	+	-	-	$\pi(1-S_1)(1-S_2)$
Y1-X1	-	+	+	$(1-\pi)(1-C_1)(1-C_2)$
Y2-X2	-	+	-	$(1-\pi)(1- C_1)C_2$
Y3-X3	-	-	+	$(1-\pi)C_1(1-C_2)$
Y4-X4	-	-	-	$(1-\pi)C_1C_2$

The probability of each cell in the 2x2 table is then the sum of two cases, i.e. true positive and true negative. For instance, p1, the probability of the two results being positive, is the sum of $\pi S_1 S_2$ and $(1-\pi)(1-C_1)(1-C_2)$.

A.3 WinBUGS program

The Bayesian latent class model was estimated using the WinBUGS code below. We provide as an example the program for the model for estimating the prevalence in adults in 2010.

```
{
y[1:K] ~ dmulti(p[1:K], n) # y is the number of patients in each cell of the two-by-two table
                           # between surgical procedure codes and ICD- 9 codes. K is the
                           # number of cells in the two-by-two table. n is the total sample size.

p[1]<- pi*(S1*S2)+(1-pi)*((1-C1)*(1-C2))
p[2]<- pi*(S1*(1-S2))+(1-pi)*((1-C1)*C2)
p[3]<- pi*((1-S1)*S2)+(1-pi)*(C1*(1-C2))
p[4]<- pi*((1-S1)*(1-S2))+(1-pi)*(C1*C2)

pi ~ dbeta(1, 1)  # non-informative prior for CHD prevalence
S1 ~ dbeta(1, 1) # non-informative prior for sensitivity of the ICD-9 codes
C1 ~ dbeta(1, 1) # non-informative prior for specificity of the ICD-9 codes
S2 ~ dunif(0.2404, 0.2768) # Prior information on sensitivity of procedures
C2 <- 1  # Prior information on specificity of procedures.
         # Procedures assumed to be perfectly specific
prev <- 1000*pi

}
# adults all list(n=6380957; K=4, y=c(6739, 41578, 3325, 6329315))
```

A.4 Methodology related to WinBUGS

The details of implementing WinBUGS and checking for convergence are as follows. We used five MCMC (Markov chain Monte Carlo) chains. For each chain, 20,000 iterations were used to estimate the parameters after 2,000 burn-in iterations. Convergence and stationary of the Markov Chains were assessed by visually inspecting the history plots for each parameter, and also using the Brooks-Gelman-Rubin method provided within WinBUGS. The point estimates of the parameters consisted of the median of the posterior samples and the 95% credible intervals were obtained by taking the 2.5^{th} and the 97.5^{th} percentiles.