MAJOR ARTICLE

Evaluation of Strategies for Use of Acellular Pertussis Vaccine in Adolescents and Adults: A Cost-Benefit Analysis

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(See the editorial commentary by Wharton on pages 29–30)

Pertussis is increasingly recognized as a source of infection in adults who then commonly infect young children. Immunity to illness caused by *Bordetella pertussis* is not long-lived, so optimal control of pertussis may require booster immunizations. In a cost-benefit analysis, we evaluated the benefits of 7 independent strategies for administering a pertussis booster, in the form of a diphtheria-tetanus-acellular pertussis vaccine, to adolescents and adults. Break-even vaccine costs for each strategy were calculated by dividing costs preventable by vaccine by the number of persons eligible for vaccination. Of these strategies, the most economical would be to immunize adolescents 10–19 years of age, which would prevent 0.7–1.8 million pertussis cases and save $0.6–$1.6 billion over a decade. Although justified by our analysis, routine adult booster vaccinations every decade would be more expensive and more difficult to implement. A recommendation for booster vaccinations every 10 years requires more information about duration of immunity, program costs, compliance, and nonmedical costs associated with pertussis.

Pertussis vaccines have been in routine pediatric use for >50 years and have dramatically decreased the incidence of whooping cough [1]. Neither vaccination nor natural infection induces long-lived immunity [2–4], so reinfections at older ages are common [5–8]. Furthermore, older contacts are often the source of infection for infants, who are at greatest risk for morbidity and mortality [9–11].

Studies of household contacts [9–11], seroprevalence [11, 12], surveillance [13–19], outbreaks [20–22], and the etiology of prolonged cough illness [23–29] suggest that pertussis infections are common among adolescents and adults. Since the 1970s, the reported incidence of pertussis, especially among adolescents and adults, has increased [13–19]. Although some increase can be attributed to increased clinical awareness, improved diagnostic methods, and better surveillance, increasing trends in the incidence of pertussis there are in all age groups [19]. Additionally, 2 recent, prospective, population-based studies of pertussis in adolescents and adults with active cough illness surveillance show the incidence of pertussis to be 450–507 cases per 100,000 person-years, accounting for more than 1 million cases nationally per year [28, 29].

Currently, in the United States, pertussis vaccine is not recommended for persons ⩾7 years of age. This relates to past concerns about the safety of whole-cell pertussis vaccines. Safer acellular pertussis (aP) vaccines have been developed and are currently in widespread pediatric use. aP vaccines have been evaluated in adolescents and adults and determined to be safe and immunogenic [28–36]. A growing appreciation of the relevance of pertussis infections beyond childhood, the recognition that adult household contacts are the main

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reservoir of infection for young children, and the availability of safe and immunogenic aP vaccines for adolescents and adults has heightened interest in developing strategies to immunize adolescents and adults [37–39]. This study evaluates health and economic benefits of 7 strategies for immunizing adolescents and adults in the United States with a combined diphtheria-tetanus-acellular pertussis (dTaP) vaccine.

METHODS

We searched the MEDLINE database to identify relevant literature published between 1966–2003 on the incidence of pertussis and pertussis-related complications, the morbidity of pertussis among persons with preexisting lung disease, household transmission of pertussis in families, and the direct and indirect costs of pertussis [5–27, 29–36, 40–44]. Cases of pertussis and complications in children 0–10 years of age were projected from published and unpublished sources (National Immunization Program, Centers for Disease Control and Prevention [CDC]; personal communication) [17]. Data from 2 prospective studies of prolonged cough illness with active pertussis surveillance were used to project the incidence of pertussis and pertussis-related complications among US persons ⩾10 years of age [28, 29].

We performed a cost-benefit analysis rather than a cost-effectiveness analysis because it is difficult to assess and compare quality-adjusted life years between population subgroups that differ in age [45, 46]. All costs were measured in 2002 US dollars, and future costs and benefits were discounted to their present value using a discount rate of 3%. Break-even vaccine costs for each strategy were calculated by dividing costs preventable by vaccine by the number of persons in the United States eligible for immunization. A break-even cost of $40 for a particular immunization strategy means that up to $40 per person can be spent on vaccine, education programs, and vaccine administration before societal costs would outweigh benefits.

To maintain adequate disease protection, it is likely that adolescents and adults require revaccination every decade. Therefore to evaluate morbidity and costs, we chose to evaluate a 10-year interval, 2001–2010. Cases of pertussis, complications, and associated direct and indirect costs were projected for this interval for infants <1 year old, children 1–9 years old, adolescents 10–19 years old, and adults 20–29, 30–39, 40–49, and ⩾50 years old.

The following 7 groups were considered for receipt of a booster immunization: (1) adolescents 10–19 years of age, (2) adults ⩾20 years of age, (3) adults ⩾50 years of age, (4) persons ⩾18 years of age with chronic obstructive pulmonary disease (COPD; asthma, chronic bronchitis, emphysema, etc.), (5) adults ⩾15 years of age who are the primary caretakers of infants <1 year of age, (6) health care workers (HCWs) ⩾20 years of age, and (7) all persons ⩾10 years of age (i.e., universal immunization). To model the effects during 2001–2010, adolescents or adults were assumed to receive dTaP once at the start of a new decade of life.

Data on the long-term efficacy of aP vaccines in adolescents and adults are lacking. We conservatively assumed that the efficacy of dTaP vaccine among adolescents and adults would be similar to that of pediatric diphtheria-tetanus-acellular pertussis (DTaP) vaccines, with an initial 88% protective efficacy that decreases to 0%–20% over a 10-year interval (mean 10-year efficacy, 50%). This estimate of protective efficacy is less than that observed in the APERT trial (92%) [28] and less than that expected with herd immunity.

Age specific mid-period populations of children, adolescents, and adults were derived from US Census Bureau population projections for 2001–2010 [47]. Statistical analysis suggests that 66%–75% of pertussis cases in infants <1 year of age and 72%–94% of cases in children 0–9 years of age are not reported [40]. We conservatively estimated that 50% of cases among US children aged 0–9 years are not reported. Base-case incidences of pertussis among children 0–9 years of age during 2001–2010 were therefore assumed to be twice as high as the incidences reported to the CDC during 1997–2000. Low estimates of pediatric incidence were assumed to be equal to reported incidences, and high estimates were assumed to be 4-fold higher than reported incidences.

APERT and another prospective study found that the incidence of prolonged pertussis cough illness among adolescents and adults was 450–507 cases per 100,000 person-years [28, 29]. Among persons 10–49 years of age with pertussis cough illness, adolescents aged 10–19 years accounted for 41% of cases, adults aged 20–29 years accounted for 7%, adults aged 30–39 years accounted for 17%, and adults aged 40–49 years of age accounted for 28%. For our sensitivity analyses, low estimates of pertussis incidence among persons ⩾10 years of age were based on laboratory-confirmed APERT cases (i.e., cases detected by culture, PCR, or both, but not by serological testing), for a total of 370 cases per 100,000 person-years. High estimates were derived from the upper boundary of the 95% CI of this estimate, for a total of 620 cases per 100,000 person-years.

The epidemiology of pertussis among adults aged ⩾65 years was not evaluated in the APERT study (which was limited to those aged 15–65 years), but it did include adults aged 49–65 years, and there was little difference in disease incidence, antibody prevalence, or estimated infection rates by age in this trial. Seroepidemiologic studies and passive surveillance suggest that adults ⩾50 years of age have at least the same incidence and morbidity as do adults 40–49 years of age [12–18, 43]. We assumed, therefore, that the incidence of pertussis among adults

aged ⩾50 years was equal to that among adults aged 40–49 years.

Rates of pertussis-related hospitalization, pneumonia, seizures, encephalopathy, and death among all age groups reported to the CDC during 1997–2000 were used to project rates of complications during 2001–2010. Low and base-case complication rates for all age groups were assumed to be equal to rates reported during 1997–2000. Because up to 91% of pertussis-related complications may not be reported for persons ⩾10 years of age, high estimates of complication rates among adolescents and adults were assumed to be 10 times higher than rates reported during 1997–2000 [40].

Mean direct costs for ambulatory and emergency department visits, antibiotics and symptom-relieving medications, and pertussis-related laboratory testing were derived from a prospective population-based survey [41]. Rates of chest radiography among persons aged ⩾10 years with pertussis cough were estimated in a retrospective study [43]. Children aged 0–9 years were estimated to undergo the same rate of chest radiography as adolescents. Children hospitalized with pertussis were assumed to spend a mean of 7 days as inpatients, adolescents aged 10–19 years were expected to spend a mean of 3 days as inpatients, and adults were expected to spend a mean of 1 day as inpatients [41, 42]. For the same 3 age categories, direct costs for complications (pneumonia, seizures, encephalopathy, and death) were calculated by adding a specific cost for each type of complication to a base-case cost for each hospitalization. Direct costs were assumed to be the same among all adults aged ⩾20 years, regardless of occupation, parental status, or preexisting COPD.

Although most episodes of pertussis cough illness in older persons are self-limited, they generate substantial indirect costs in time lost from work and other activities. For example, during a pertussis outbreak, mean losses among adolescents and adults with pertussis were 5 school days and 7 workdays, respectively, and at least 10% of these adolescents and adults had relatives who lost an additional mean of 1–5 school days or workdays [43]. We estimated that adults lose a mean of 2 workdays to care for a child with pertussis, 16 h to care for an adolescent, and 28 h to care for an adult. Mean base-case estimates of time lost from other cost-generating activities (social and/or recreational activities) were assumed to be a 4 days per child, 16 h per adolescent, and 28 h per adult.

Costs for pertussis complications also result in long-term losses in productivity and were derived from previous economic analyses of the value of work and non–work-related activities to society [48, 49]. We assumed that 1% of cases of pertussis-related encephalopathy among children, adolescents, or adults would result in permanent brain damage (significant cognitive impairment, motor impairment, or both). Mean base-case values for complication-related indirect costs were $20,000 per case for encephalopathy [42], $2.4 million per case for encephalopathy with permanent brain damage [48], and $5 million per death [49].

Relative to base-case estimates, low and high estimates of indirect costs were 67% and 150%, respectively. Cost assumptions for children, adolescents, and adults are summarized in table 1.

Household transmission to infants <1 year of age. Infants <1 year of age who have not received 3 doses of aP vaccine comprise those at greatest risk for morbidity and mortality. Up to 70% of infections in this age group are transmitted from adult and adolescent household contacts [9–11]. Therefore, it is plausible that immunizing infant caretakers might significantly decrease pediatric morbidity and mortality.

The number of relevant households was obtained from 2000 US Census Bureau data [50]. The base-case household caretaker transmission rate was assumed to be 40%; that is, 40% of infants <1 year old were assumed to acquire pertussis from their primary household caretaker aged ⩾15 years [11]. The low estimate of this transmission rate was 30%, and the high estimate was 50%. We did not assume a higher vaccine efficacy for infant caretakers or assign any temporal relationship between the immunization of caretakers and the birth of infants.

Persons with COPD. US Census Bureau projections and National Center for Health Statistics data were used to estimate the number of persons ⩾18 years with COPD [47, 51]. Data on pertussis in individuals with preexisting lung disease are limited. In one study, adolescents and adults who smoked tobacco or had asthma coughed 7 days longer than did persons without these conditions, but the frequencies of pertussis and its complications were not significantly different between groups [43]. Persons aged ⩾18 years with COPD were therefore assumed to have the same incidence, morbidity, and direct costs as persons aged ⩾18 years without COPD, but indirect costs among persons with COPD were projected to be >7 additional days of work and social productivity lost, combined.

HCWs. The number of HCWs ⩾20 years of age during the year 2000 was ascertained from the US Bureau of Labor Statistics [52]. The numbers and types of HCWs aged ⩾20 years during 2001–2010 were assumed to be similar to those during 2000. We did not attempt to model the transmission of pertussis from HCWs to patients, and we conservatively assumed that the incidence of pertussis and complications among HCWs was equal to the incidence among non-HCWs. HCWs with pertussis were assumed to have additional lost work, because infection-control policies recommend that symptomatic HCWs be furloughed for 5 days while taking antibiotics [53]. Up to 20% of symptomatic HCWs are furloughed, so we assumed as a base case that 20% of HCWs lose 5 days from work and that the remaining 80% of HCWs lose no time from work [44]. Our low estimate of the HCW symp-

Table 1. Age-specific cost estimates, in US dollars, for pertussis and pertussis-related complications.

Cost	Children	Adolescents	Adults
Direct outpatient costs			
Office/emergency department visit	127.76	105.52	67.50
Medication, mean			
Antibiotics	17.00	18.48	16.50
Symptom relief	5.98	3.97	…
Total	22.98	22.45	16.50
Procedure/test			
Chest radiography, total	70	70	70
Mean per person[a]	35.00	16.80	21.70
Pertussis-related testing, mean per person	38.93	29.86	35.33
Total per person	73.93	46.66	57.03
Direct inpatient costs			
No. of inpatient days	7	3	1
Total per inpatient day	1100	1100	1100
Base-case hospitalization	7700	3300	1100
Additional, by illness			
Seizures	4000	3000	2000
Pneumonia	2000	1300	1000
Encephalopathy	6000	5000	4000
Terminal	20,000	17,000	12,000
Indirect			
Activity			
Work, hours	48	16	28
Other activities, hours	96	16	28
Total, per hour of activity	22	22	22
Overall (base-case estimate)	3168	704	1232
Societal costs			
Per case of encephalopathy	20,000	20,000	20,000
Per case of PBD[b]	2,400,000	2,400,000	2,400,000
Per death	5,000,000	5,000,000	5,000,000

NOTE. PBD, permanent brain damage.

[a] Determined on the basis of radiographic testing of 50% of children, 24% of adolescents, and 36% of adults.

[b] Among patients with PBD (encephalopathy) from pertussis, 1% of children, 1% of adolescents, and 1% of adults develop PBD.

tomatic pertussis furlough rate was 10%, and the high estimate was 30%.

Vaccine safety costs. aP vaccines designed to be administered to adolescent and adults (dTaP) have lower doses of pertussis antigens than do pediatric aP vaccines but have similar immunogenicity. Rates of adverse reactions to aP are also less frequent among adults, compared with children [28, 30, 33]. Limb swelling—a reaction documented among children who receive ⩾4 doses of pediatric DTaP—has not to date been observed in adults. Detailed vaccine safety data from the APERT trial, during which >1300 persons aged 15–65 years received aP vaccine, indicate that the vaccine induced no adverse reactions requiring medical attention. In a smaller trial, 510 adolescents who received dTaP showed no differences in local or systemic reactions, compared with control subjects who received dT [30]. The rate of dTaP adverse events is not nil, so we assumed that 1% of persons aged ⩾10 years might require medical attention for local or systemic reactions attributable to DTaP and that 1 medical visit would cost $200 for evaluation.

Compliance with recommended dT vaccination among adolescents and adults in the United States is low. As a plausible estimate, we assumed that 40% of adolescents and adults in the United States would receive dTaP during the 10-year study period. The minimum compliance with vaccination was assumed to be 20%, and the maximum compliance was set at 100%.

Table 2. Projections of the number of cases of pertussis cough illness and associated complications, direct costs, indirect costs, and total costs by age, 2001–2010.

Age in years	No hospitalization	Hospitalization	Pneumonia	Seizure	Encephalopathy	Death	Total
<1, No. of patients	31,088	12,111	2348	276	41	143	43,199
Direct cost	6985	93,255	4696	1104	246	2860	109,146
Indirect cost	98,487	38,368	7438	874	1934	715,000	862,101
Total	105,472	131,263	12,134	1978	2180	717,860	971,247
1–9, No. of patients	29,373	1025	590	123	3	8	30,398
Direct cost	6599	7893	1180	492	18	160	16,342
Indirect cost	93,054	3247	1869	390	142	40,000	138,702
Total	99,563	11,140	3049	882	160	40,160	155,044
10–19, No. of patients	3,687,352	436	388	63	8	0	3,687,788
Direct cost	643,922	1439	504	189	40	…	647,094
Indirect cost	2,595,896	307	273	44	358	…	2,596,878
Total	3,239,818	1746	777	233	398	…	3,242,972
20–29, No. of patients	614,556	75	45	15	0	0	614,631
Direct cost	86,671	83	45	30	…	…	86,829
Indirect cost	757,133	92	55	18	…	…	757,298
Total	843,804	175	100	48	…	…	844,127
30–39, No. of patients	1,536,453	125	73	25	3	0	1,536,578
Direct cost	216,686	138	73	50	12	…	216,959
Indirect cost	1,892,910	154	90	31	136	…	1,893,321
Total	2,109,596	292	163	81	148	…	2,110,280
40–49, No. of patients	2,458,412	113	125	25	3	3	2,458,525
Direct cost	346,710	124	125	50	12	36	347,057
Indirect cost	3,028,764	139	154	31	136	15,000	3,044,224
Total	3,375,474	263	279	81	148	15,036	3,391,281
⩾50, No. of patients	4,736,878	193	126	15	3	3	4,737,071
Direct cost	668,042	212	126	30	12	36	668,458
Indirect cost	5,835,834	238	155	18	136	15,000	5,851,381
Total	6,503,876	450	281	48	148	15,036	6,519,839
Overall, No. of patients	13,094,112	14,078	3695	542	61	157	13,108,190
Direct cost	1,975,615	103,144	6749	1945	340	3092	2,090,885
Indirect cost	14,302,078	42,545	10,034	1406	2842	785,000	15,143,905
Total	16,277,693	145,689	16,783	3351	3182	788,092	17,234,790

NOTE. Data are thousands of 2002 US dollars, unless otherwise indicated.

Methods for the calculation of low and high model parameters (i.e., compliance with vaccination, incidence of pertussis among adolescents and adults, direct and indirect cost estimates, household transmission rates to infants, adjustment of adolescent and adult complication rates for underreporting, adjustment of pertussis incidence among children due to underreporting, and rates of furlough among HCWs) are presented. A multivariate sensitivity analysis for a universal vaccination strategy (i.e., vaccination of all US adults and adolescents at least once during the study period) was performed by varying these individual model parameters simultaneously between their low and high estimates.

RESULTS

The projected annual incidence of pertussis assuming steady rates of vaccination among infants <1 year of age was 55–220 cases per 100,000 infant-years. Among children aged 1–9 years, the incidence was 4.4–17.7 cases per 100,000 child-years. The base-case incidence of pertussis cough illness among adolescents aged 10–19 years was 885 cases per person-years and, among adults aged 20–29 years, 30–39 years, ⩾40 years of age, was 159, 399, and 548 cases per 100,000 person-years, respectively.

It was projected that, during 2001–2010, infants <1 year old accounted for at least 43,199 pertussis cases (0.3%), children aged 0–9 years accounted for 30,398 cases (0.2%), adolescents aged 10–19 years accounted for 3,687,788 cases (28%), and adults aged ⩾20 years accounted for 9,346,805 cases (71%). Among persons in the United States aged ⩾10 years, adolescents aged 10–19 years accounted for 436 pertussis-related hospitalizations (46%), 388 cases of pneumonia (51%), 63 cases resulting in seizures (44%), and 8 cases of pertussis-related

encephalopathy (47%), but there were no cases of permanent brain damage or death. Adults aged ⩾50 years accounted for 21% of hospitalizations, 17% of pneumonia cases, 10% of seizure cases, 18% of encephalopathy cases, and more than one-half of all deaths among persons aged ⩾10 years (table 2).

Direct, indirect, and total costs of pertussis by age group are listed in table 2. Overall, infants <1 year old accounted for 5%, adolescents accounted for 31%, and adults aged ⩾50 years accounted for 32% of direct (medical) costs. With respect to indirect costs, infants <1 year of age accounted for 6%, adolescents aged 10–19 years accounted for 17%, and adults aged ⩾50 years accounted for 39%. Among all persons in the United States hospitalized because of pertussis, infants <1 year of age accounted for 89% and 91% of direct and indirect costs, respectively. Inpatients of all ages accounted for only 5% and 6% of direct and indirect costs, respectively. Nonhospitalized patients with pertussis accounted for 11% of all costs among infants <1 year of age but for 64% and >99% of all costs among children aged 0–9 years and persons aged ⩾10 years. Among persons aged ⩾10 years, non–work-related costs accounted for $7.1 billion, or one-half of all indirect costs ($14.1 billion). Among all persons aged ⩾10 years in the United States, indirect costs accounted for 88% of total pertussis-related costs.

Costs Preventable by Vaccine and Break-Even Costs per Vaccination

Adolescents and adults. Over a 10-year period, immunization of all adolescents aged 10–19 years in the United States with aP vaccine might prevent 0.4 million to 1.8 million adolescent pertussis cases and save $0.3 billion to $1.6 billion. Vaccination of all adults aged ⩾20 years during each decade of life over the same interval might prevent 0.9 million to 4.7 million adult cases and save $1.3 billion to $6.4 billion. Vaccination of adults aged ⩾50 years might prevent 0.5 million to 2.4 million cases of pertussis among older adults and save $0.7 billion to $3.3 billion nationally. Vaccination of all persons aged ⩾10 years might prevent 1.3 million to 6.5 million cases of pertussis during 2001–2010, including 3000–15,000 cases among infants <1 year of age (assuming that 70% of infants

Table 3. Univariate sensitivity analysis for a universal vaccination strategy, 2001–2010

Parameter, base-case estimate	Cost preventable by vaccination, millions of 2002 US dollars	Break-even cost per vaccination, millions of 2002 US dollars
Compliance with vaccination at each decade of life, 40%	4843	31.68[a]
Low estimate of 20%	2421	…
High estimate of 100%	12,108	…
Annual incidence of pertussis, persons ⩾10 years of age, 450[b]		
Low estimate of 370	6993	25.96
High estimate of 620	11,458	43.82
Indirect costs, 100%		
Low estimate of 67%	5988	21.95
High estimate of 150%	12,108	46.42
Direct costs, 100%		
Low estimate of 67%	8085	30.33
High estimate of 150%	8932	33.72
Rate of transmission from parents to infants, 40%		
Low estimate of 30%	8337	31.34
High estimate of 50%	8507	32.02
Adjustment factor for pertussis complications, 1		
Low estimate of 1	8422	31.68
High estimate of 10	11,198	42.78
Adjustment factor for underreporting among children, 2[c]		
Low estimate of 1	8396	31.57
High estimate of 4	8473	31.88
Health care workers furloughed, 20%		
Low estimate of 10%	8408	31.62
High estimate of 30%	8435	31.73

[a] Break-even costs per individual vaccinated do not vary with the number of individuals who comply with vaccination.
[b] Incidences are new cases of pertussis per 100,000 person-years.
[c] Children aged 0–9 years during 2001–2010.

acquire infection from older household contacts). Excluding vaccination expenses, universal vaccination could save $1.6 billion to $8.4 billion per decade. Using base-case model assumptions, the (break-even) costs of adolescent and adult pertussis vaccination programs could reach as high as $36.92 and $28.86, respectively, before the societal costs of pertussis vaccination outweigh societal benefits (tables 3 and 4).

Household caretakers of young infants. Over the 10-year study period, we estimate that there would be 39 million persons aged ⩾15 years who were primary caretakers of infants <1 year of age. If these caretakers were immunized, 160,000–801,000 pertussis cases among caretakers and 1700–8600 cases among infants <1 year of age might be prevented. Six to 32 infant deaths would be prevented, and $0.2 billion to $1.2 billion would be saved. The break-even vaccine cost for each primary caretaker would be $29.24.

HCWs. A total of 4,460,000 HCWs in the United States might receive DTaP vaccine over a 10-year period. Immunization of HCWs each decade would prevent 20,000–100,000 cases of pertussis and would save $30 million to $151 million, excluding costs avoided by interrupting the transmission of pertussis from HCW to young infants, debilitated persons, and older adults. Excluding benefits saved by preventing nosocomial outbreaks of pertussis, the break-even vaccine cost for HCWs would be $31.94.

Persons with COPD. Over a decade, if all adults in the United States aged ⩾18 years with COPD were immunized against pertussis, 768,000 cases of pertussis might be prevented, and more than $1.3 billion could be saved. Because of the additional time lost by adults with COPD to prolonged cough illness, the break-even vaccine cost would be $36.43.

Sensitivity Analyses

Table 3 depicts base-case values and a sensitivity analysis for a universal vaccination strategy performed by varying individual model parameters simultaneously to their respective low and high values. Vaccination would have the greatest value for adolescents aged 10–19 years, followed by adults aged ⩾18 years with COPD, adults aged ⩾50 years, HCWs, all persons aged ⩾10 years, household caretakers of infants <1 year of age, and adults aged ⩾20 years. Although not much different, base values for break-even vaccination costs would be greatest for the strategy of adolescent immunization ($36.92) and least for immunizing adults aged ⩾20 years ($28.86). These break-even costs include the costs associated with caring for adverse events ($200 for 1% of the US population aged ⩾10 years, or $2 per individual aged ⩾10 years), assuming that all eligible persons comply with recommended dTaP immunization.

A multivariate sensitivity analysis of vaccine-preventable costs and break-even costs is presented in table 4. Variations in compliance with vaccination most strongly influence vaccine-preventable costs followed by, in order of importance, the incidence of pertussis among adolescents and adults, variations in indirect cost estimates, variations in direct cost estimates, secondary transmission to infants, rates of underreporting of complications, rates of underreporting of pediatric cases of pertussis, and rates of furlough among HCWs.

DISCUSSION

Similar to what has been seen with influenza, most pertussis-related costs are not due to the direct costs of pertussis or its complications but, rather, to lost productivity at work and social activities (i.e., indirect costs). Although immunization of special subgroups, notably older adults, persons with COPD, and caretakers of young infants, vaccination is likely to be cost beneficial; our model most strongly supports the immunization of adolescents 10–19 years of age. Vaccination is most cost-effective among adolescents because they have the highest incidence of pertussis and pertussis-related complications. Compliance with vaccination would be higher in states where documentation of dT immunization is required before entry into middle

Table 4. Break-even costs per vaccination with multivariate sensitivity analysis.

Vaccination strategy, by vaccinee group	Projected US population	Cost per vaccination, US$		
		Break-even	Low estimate[a]	High estimate[a]
All adolescents 10–19 years of age	41,658,000	36.92	13.01	111.22
Adults ⩾18 years of age with COPD	33,725,000	36.43	12.83	110.04
All adults ⩾50 years of age	86,375,000	35.74	12.56	107.13
Health care workers	4,458,000	31.94	10.98	94.44
All persons ⩾10 years of age (universal vaccination)	250,075,000	31.68	10.92	123.83
Household caretakers of infants <1 year of age[b]	38,680,000	29.24	9.75	192.47
All adults ⩾20 years of age	208,417,000	28.86	9.91	87.98

NOTE. COPD, chronic obstructive pulmonary disease.

[a] Defined in Methods.

[b] Population and cost estimates are based on projected primary caretakers of infants <1 year of age who were ⩾15 years of age during 2001–2010.

school, and the addition of an aP vaccine to the already recommended adult dT vaccine could lower the administrative and programmatic costs of a national dTaP booster policy.

Among adults, severe complications of pertussis are most frequent among older persons [13, 14]. Descriptions of the transmission of pertussis from grandparents to grandchildren have been published, and outbreaks of pertussis occur among older adults [54, 55]. If complications are more frequent among persons ⩾65 years and if outbreaks occur in this population, then older adults might be another potential group for which immunization might be appropriate. Additional prospective data on pertussis in older individuals might strengthen recommendations to immunize these groups.

The long-term efficacy of aP vaccine in adolescents and adults is unclear, and, because herd immunity is difficult to model, we were not able to predict the long-term protection from booster immunization or the optimal window for revaccination. If aP vaccination of adolescents and adults is cost-effective and if immunization is performed once per decade, the health and economic benefits should accumulate over time. Increasing herd immunity may prove to increase the benefit of aP immunization beyond what we have postulated.

Our study had limitations that were based on the lack of relevant data in the literature. We had little prospectively ascertained data on direct or indirect disease costs, including loss of work and social productivity. Aside from the cost of illness estimates based on a survey we conducted of individuals with prolonged cough illness (not necessarily pertussis), we did not have definitive data on the cost of illness. Also, we could not assess the prevention of secondary transmission in households. Nonetheless, our conclusions should be applicable to all aP vaccines.

In summary, we evaluated pertussis-related morbidity, cost, and relative cost-benefit data of immunization strategies for 7 groups of individuals. Immunizing adolescents aged 10–19 years is the most economical strategy and would be easiest to implement, particularly if a combination dTaP vaccine replaced the currently recommended dT vaccine. Compliance with dT immunization as high as 40% among adolescents aged 10–19 years implies equivalent compliance with dTaP. Even with conservative assumptions, dTaP immunization of older adults, persons with COPD, household caretakers of young infants, and HCWs would also provide significant health and economic benefits. Additional data on the costs of immunizing special groups of adolescents and adults and more precise quantification of indirect costs would be useful in refining a cost-benefit analysis of pertussis vaccination.

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