

The Social Value of Childhood Vaccination in the United States

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The innovation of childhood vaccines has resulted in a decline in infectious disease, as well as gains in length and quality of life. Smallpox has been eradicated, poliomyelitis is nearly eliminated, and many other vaccine-preventable diseases have seen declines in incidence.¹⁻³ Although adverse events (AEs) can occur with vaccines,⁴⁻⁷ and recent research has focused on their rising costs,⁸⁻¹⁰ the postvaccine era has seen life expectancy increase 15 to 25 years compared with the pre-vaccine era, and further gains are expected.^{3,11} Evidence suggests a large share of these survival gains is due to the control of infectious disease through vaccination.³

When encouraged by public health policies, vaccination also provides a benefit to government and private payers by reducing overall costs and increasing population health. The CDC has cited evidence that common childhood vaccinations save over \$5 in direct medical costs and effects on productivity for every \$1 spent.¹² Maciosek and colleagues found that preventative childhood immunization produced annual net medical savings of \$267 per person.¹³ Vaccination also generates community (herd) immunity by reducing disease incidence and transmission, thus resulting in a healthier population.¹⁴

Because vaccines have been successful at preventing disease, the public is no longer regularly confronted with many vaccine-preventable diseases, and the health and economic benefits of vaccination may be underappreciated.¹⁵ As childhood vaccines have reduced disease prevalence, real and perceived AEs of vaccination have become more salient to parents than the vaccine-targeted diseases.^{16,17} Consequently, vaccination rates in many US states have declined in recent years.¹⁷ As vaccination rates slip, the risk of new outbreaks increases.¹⁸

Moreover, although consumers are insulated from the cost of many vaccines, vaccine cost is an important consideration for payers and providers and has been criticized.¹⁹ This focus on AEs and costs has obscured vaccines' overall value to individuals and society. Previous research has yet to show how the total social value of vaccines is divided between innovators who develop these

ABSTRACT

OBJECTIVES: To determine the lifetime social value of using the guideline-recommended vaccines for children born in the United States in 2009.

STUDY DESIGN: This study utilized an economic model with parameter values sourced from clinical and observational data, as well as the literature.

METHODS: The model quantified the health effects of routine vaccination for 14 diseases in terms of quality-adjusted life-years (QALYs) saved. The health effects were then valued by applying an economic value of a QALY. Producers' profits were estimated using data on vaccine prices, profit margins, and the number of vaccines administered in the 2009 US birth cohort. The costs of producing the vaccines were subtracted from the value of the health effects to yield the total social value of vaccination. The producers' and consumers' shares of this social value were calculated. Sensitivity analyses were conducted to determine how results depend on underlying parameter assumptions.

RESULTS: Estimates indicated that vaccination of this cohort will save 1.2 million QALYs, relative to no vaccination. Of those health gains, 88% stemmed from reduced mortality and 12% from reduced morbidity. We estimated a social value of \$184.1 billion from these gains, of which \$3.4 billion accrues to manufacturers as profits, while \$180.7 billion accrues to the rest of society. In sensitivity analysis, the total social value ranged from \$40 billion to \$675 billion, and the manufacturers' share ranged from 0.3% to 11.5%.

CONCLUSIONS: Policy makers should account for this social value when considering policies affecting incentives to vaccinate and develop new vaccines.

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technologies and patients and the broader society who benefit from them. Therefore, in this study, we sought to measure the social value of childhood vaccines in the United States and the distribution of that value to manufacturers versus the rest of society.

The concept of social value of therapies and its distribution between manufacturers and patients has been described in other disease areas. For instance, Grabrowski et al found that statin usage resulted in a social value of \$1.25 trillion, of which patients received 76%.²⁰ Yin et al performed a similar analysis on tyrosine kinase inhibitors for the treatment of chronic myeloid leukemia and found a social value of \$143 billion—90% of which was retained by patients.²¹ Recent gains in cancer survival have provided \$1.9 trillion of additional social value, with 81% to 95% of that being retained by patients.²² Lastly, HIV/AIDS therapies have generated \$1.38 trillion in social value, with 95% accruing to patients.²³ Such analyses are net monetary benefit analyses, which is a common economic way of thinking about value which is distinct from cost-effectiveness analysis. The aim is to measure the total value a given health intervention generates for society, and how that value is distributed across patients and manufacturers.

This study applied similar methods to determine the social value of childhood vaccines for a birth cohort in the United States. Consistent with previous research, social value was defined from an economic perspective as the quantity of resources, in monetary terms, that society would be willing to give up in order to retain the health gains attributable to vaccines. Put another way, the overall social value of vaccines equals the aggregate value retained by consumers (above the actual payments for vaccines) plus the value retained by manufacturers (in the form of vaccine profits). We decomposed the social value into the shares accruing to manufacturers versus the rest of society. For infectious diseases, the social value includes not only those vaccinated, but also those not vaccinated who benefit from the reduction in disease incidence.¹⁵

METHODS

Overview

The study entailed constructing an economic model based on observational and clinical data. The model calculates the social value of the routine pediatric vaccination schedule used in the United States in 2009. We do so by quantifying the health effects of routine vaccination of children born in the United States in 2009. In particular, vaccines to prevent the following 14 diseases were considered: congenital rubella syndrome, diphtheria, haemophilus influenzae type b (Hib), hepatitis A, hepatitis B, measles, mumps, pertussis, pneumococcus-related diseases (including pneumococcal disease, otitis media, pneumonia,

and meningitis), polio, rotavirus, rubella, tetanus, and varicella. The influenza vaccine was not included because its changing seasonal nature would have required different methods.

The social value was estimated by applying an economic value to the health effects of vaccines, measured in terms of quality-adjusted life-years (QALYs) saved through vaccination. QALYs take into account both duration and quality of life. A year in perfect health would be measured as 1 QALY, whereas death counts as 0. From the value of the QALYs gained, the costs to produce vaccines were subtracted. This yielded the social value—or in economic terms, the total surplus—of vaccines, and represents the economic value of the health gains from vaccines minus the resources society spent to produce them. The shares of the total surplus accruing to manufacturers (producer surplus) versus the rest of society (consumer surplus) were also calculated.

It should be noted that vaccine-preventable illnesses impose additional costs on society beyond the utility loss infected individuals experience, including caregiver utility loss and the use of special services for persistent disability. Therefore our estimate of the health value of vaccination should be considered a lower bound.

In addition, one should exercise caution in interpreting the results of this framework for rotavirus, since in industrialized countries like the United States, the costs of rotavirus are mainly hospitalization and caregiver utility loss, as rotavirus mortality and morbidity are lower in the industrialized setting. In contrast, many of the other studied vaccines target illnesses that imposed a high mortality and morbidity burden in the pre-vaccine era.²⁴

Data Sources

According to the CDC, 4,130,665 children were born in the United States in 2009.²⁵ The health effects of vaccination in this cohort were estimated by combining data from the literature with life tables from the Human Mortality Database.²⁶ From the literature, we obtained for each disease data on cases of illness prevented, premature deaths avoided, average age of onset, average age at death from the disease, average duration of disease, and utility loss. Specific parameter values and sources are available in the [eAppendix](#) (eAppendices available at www.ajmc.com). The survival benefits of vaccination were net of adverse reactions to vaccination. To obtain the economic

TAKE-AWAY POINTS

- ▶ By preventing illness and premature deaths, vaccination of children born in the United States in 2009 will generate \$184 billion in lifetime social value above the costs of the vaccines.
- ▶ Because saving a child's life yields many healthy life-years, the large majority (88%) of the health benefits of vaccines is due to avoided premature deaths rather than reduced morbidity (12%).
- ▶ The high social value of vaccines has improved population health and provided economic benefit to multiple stakeholders, including patients, health plans, and vaccine manufacturers, whose profits in this cohort amount to approximately 2% (\$3.2 billion) of the total social value.

value of a QALY, we considered values generated by revealed and stated preference studies.^{27,28} A mid-range value of \$150,000 was used and varied in sensitivity analysis.

Estimating manufacturers' profits required 3 types of data: 1) data on vaccine prices, 2) data on manufacturers' profit margins, and 3) data on the number of vaccines administered in the 2009 US birth cohort. We obtained data on prices (available in the eAppendix) from the CDC Vaccines for Children Program website, which contains archived data on public and private vaccine prices from 2008 to 2015.²⁹

We obtained data on vaccine manufacturers' profit margins from annual reports and financial statements. When measuring manufacturers' profits, we used the gross profit margin, which represents the sales volume minus production costs. Obtaining a companywide average across the top 5 vaccine manufacturers produced an average gross profit of 75%.³⁰⁻³⁴ This is a conservative approach, as gross profits do not subtract out manufacturer research and development (R&D) and marketing expenses. By using the gross profit margin, we can view vaccines' social value as society's benefit from vaccination, and society's investment in R&D as the cost of inventing and developing the vaccines. (Subtracting R&D from profits would negate this framing.) This framing is useful because investments should be undertaken when the benefits (ie, the return on investment) exceeds the cost; social value is an important part of this equation. Moreover, R&D costs include the costs of many failures that the innovator encountered on the way to the given successful product; there is not an established method for measuring R&D costs for vaccines.

To estimate the number of vaccines administered, we required data on vaccine coverage rates, dosage schedules, wastage, and the cohort size. Following previous work, we assumed that 53% of vaccine doses were publicly (vs privately) administered and the wastage rate—the rate at which additional vaccines must be purchased beyond those needed for each vaccinated child because some vaccines will be unused—was 5%.³⁵ We obtained vaccination rates,³⁶ the recommended vaccination schedule,³⁷ and the size of the cohort²⁵ from the CDC. Doses administered between ages 0 and 18 were included, but the costs of any adult booster doses were excluded. Given that any adult booster doses occur many years into the child's life, whereas the lives saved and illnesses avoided from vaccination are realized mainly in early childhood, the effect of the focus on childhood doses should be minimal.

Analysis

The 3 analytic steps are described broadly below. Additional detail is provided in the eAppendix. Throughout the analysis, monetary values were inflation-adjusted to 2014 US dollars using the Consumer Price Index,³⁸ and an annual discount rate of 3% was applied.

Step 1: Value Health Effects of Vaccination

The health effects of vaccines were calculated by summing the changes in morbidity and mortality among the 2009 US birth cohort due to

vaccination. The mortality effects were calculated as the number of deaths averted from vaccination multiplied by the QALYs the typical child would lose from dying of the given disease (calculated as average life expectancy minus average age at death from the given disease times aged-adjusted utility). The morbidity effects were calculated as the number of cases of illness prevented through vaccination times the typical duration of illness times the disutility from the given illness. The health effects of vaccines in QALYs were then converted to economic terms by valuing each QALY at \$150,000.³⁹⁻⁴¹ This yielded the economic value of the health effects of vaccination.

Step 2: Estimate Manufacturers' Profits

Vaccine manufacturers' profits from a given vaccine were estimated by multiplying the vaccine's price by the number of vaccines sold by the profit margin. Although vaccines typically consist of multiple doses, and vaccination rates vary by dose, in the profit calculations we assumed that all children who received the first dose of a vaccine would also receive all subsequent doses. This assumption overestimates profits because some children will not receive all doses, and manufacturers' profits will be lower than they would be had these children received all of their doses.

Step 3: Calculate Total Value

Using the results of the previous 2 steps, we calculated consumer, producer, and total surplus (ie, social value). Consumer surplus was calculated as the value of the health effects of vaccines (from Step 1) minus the cost of the vaccines (from Step 2). Producer surplus equaled the manufacturer profits (from Step 2). Consumer and producer surplus together yielded the total surplus.

Sensitivity Analyses

We performed analyses to test the sensitivity of the model to the parameters. Specifically, we varied all parameters by $\pm 10\%$, except for the disease-specific vaccination rates, which were varied by $\pm 5\%$ to avoid specifying rates over 100%. In addition, we also varied the value of a QALY from \$50,000 through \$250,000 to reflect the wide range of values in the literature, and varied the discount rate from 0% to 6%. Lastly, we conducted an analysis, which included the parents' time cost to take the children to receive the vaccines, taking into account that multiple vaccines may be given in the same visit.

RESULTS

The health effects of vaccination are reported in **Table 1**. Compared with no vaccination, an estimated 1.2 million QALYs will be saved due to vaccination among children born in the United States in 2009, for a value of \$185.2 billion. Because vaccines typically prevent deaths that would have occurred in childhood, these avoided deaths save a large number of QALYs, whereas QALY gains from avoided illness are more modest. Consequently, 88% of the health

TABLE 1. Health Effects of Vaccination

Disease	Morbidity Reductions (QALYs)	Mortality Reductions (QALYs)	ΔQALYs Due to Vaccines	Health Value (\$ millions ^a)	Avoided Illness (\$ millions ^a)	Avoided Death (\$ millions ^a)	Avoided Illness	Avoided Death
DTaP/Tdap	44,551	751,038	795,589	119,338	6683	112,656	6%	94%
Hib	331	19,415	19,746	2962	50	2912	2%	98%
Hepatitis A	17,616	714	18,330	2750	2642	107	96%	4%
Hepatitis B	1891	77,444	79,336	11,900	284	11,617	2%	98%
MMR	50,642	83,955	134,597	18,614	6021	12,593	32%	68%
Pneumococcus-related diseases	17,014	137,088	154,103	23,115	2552	20,563	11%	89%
Polio	194	17,631	17,825	2674	29	2645	1%	99%
Rotavirus	4749	515	5264	790	712	77	90%	10%
Varicella	18,740	1785	20,525	3079	2811	268	91%	9%
Combined all 9 vaccines	155,729	1,089,586	1,245,315	185,221	21,784	163,438	12%	88%

DTaP/Tdap indicates diphtheria, tetanus, and [acellular] pertussis; Hib, haemophilus influenza type B; MMR, measles, mumps, rubella, and congenital rubella syndrome; QALYs, quality-adjusted life-years.

^aMonetary values are expressed in 2014 US dollars.

Source: Authors' calculations.

value of vaccines is due to avoided death compared with 12% due to avoided illness. Among vaccines, diphtheria, tetanus, and pertussis (DTaP/Tdap) will have the largest health value by an order of magnitude, at nearly 800,000 QALYs saved for a value of \$119 billion. Other vaccines with large health values are pneumococcus-related diseases (154,000 QALYs, \$23 billion); measles, mumps, and rubella (MMR) (135,000 QALYs, \$19 billion); and hepatitis B (79,000 QALYs, \$12 billion). The smallest health value will be for rotavirus, at 5264 QALYs and \$790 million.

Table 2 reports estimates of manufacturers' revenues, costs, gross and net profits by vaccines given to the 2009 US birth cohort. Estimated profits are the lowest for the hepatitis A vaccine (\$109 million gross, \$36 million net), and the highest for pneumococcus-related diseases (\$1.0 billion gross, \$350 million net). Across all 14 diseases, vaccines generate an estimated \$4.5 billion in revenues, \$1.1 billion in costs, \$3.4 billion in gross profits, and \$1.1 billion in net profits.

The total social value by vaccine and its distribution across manufacturers and consumers are reported in **Table 3**. Consumers' share of value, or surplus, ranges from \$10 million for rotavirus to \$119 billion for DTaP/Tdap. Vaccines producing the greatest consumer surplus do not necessarily provide the largest profit, or producer surplus, to manufacturers. Total social value ranges from \$595 million from rotavirus to \$119 billion from DTaP/Tdap, with the full vaccination schedule generating \$184 billion in social value

(**Figure 1**), or \$45,000 per child. Of that total social value, 1.8% accrues to manufacturers, whereas 98.2% accrues to the rest of society. The manufacturers' share ranges from 0.3% for DTaP/Tdap to 98.3% for rotavirus, and is less than 15% for 7 out of the 9 vaccines.

In sensitivity analyses, we found that the model is most sensitive to the economic value of a QALY, the premature deaths prevented from vaccination, and the discount rate, which together contributed 98.1% of the variance in results (**Figure 2**). In simulations, the total social value ranged from \$153 billion to \$227 billion, and the

TABLE 2. Estimated Manufacturer Revenues, Costs, Gross and Net Profits, by Vaccine^a

	Revenue (\$ millions ^b)	Costs (\$ millions ^b)	Gross Profit (\$ millions ^b)	Net Profit (\$ millions ^b)
DTaP/Tdap	460	115	345	115
Hib	279	70	209	70
Hepatitis A	145	36	109	36
Hepatitis B	218	54	163	54
MMR	262	65	196	65
Pneumococcus-related diseases	1399	350	1049	350
Polio	317	79	237	79
Rotavirus	780	195	585	195
Varicella	614	153	460	153
Combined all 9 vaccines	4472	1118	3354	1118

DTaP/Tdap indicates diphtheria, tetanus, and [acellular] pertussis; Hib, haemophilus influenza type b; MMR, measles, mumps, rubella, and congenital rubella syndrome.

^aGross profit margins are sales revenue minus production costs. Net profit margins also take out research and design, marketing, and other expenses. Profit estimates assume average companywide profitability rates from the top 5 vaccine manufacturers apply to each vaccine, and should thus be viewed as approximations. Profit calculations also assume that any child who receives the first dose of a vaccine will receive the full schedule, which makes the profit estimates an upper bound.

^bAll monetary values are expressed in 2014 US dollars.

Source: Authors' calculations.

TABLE 3. Social Value and the Shares Accruing to Manufacturers and the Rest of Society^a

Disease	Consumer Surplus (\$ millions ^b)	Producer Surplus (\$ millions ^b)	Social Value (\$ millions ^b)	Manufacturer Share of Social Value	Share to Rest of Society
DTaP/Tdap	118,879	345	119,223	0.3%	99.7%
Hib	2683	209	2892	7.2%	92.8%
Hepatitis A	2604	109	2713	4.0%	96.0%
Hepatitis B	11,683	163	11,846	1.4%	98.6%
MMR	18,352	196	18,548	1.1%	98.9%
Pneumococcus-related diseases	21,717	1049	22,766	4.6%	95.4%
Polio	2357	237	2595	9.1%	90.9%
Rotavirus	10	585	595	98.3%	1.7%
Varicella	2465	460	2925	15.7%	84.3%
Combined all 9 vaccines	180,750	3354	184,103	1.8%	98.2%

DTaP/Tdap indicates diphtheria, tetanus, and [acellular] pertussis; Hib, haemophilus influenza type b; MMR, measles, mumps, rubella, and congenital rubella syndrome.
^aProducer surplus is measured as gross profits and assumes any child who received the first dose of a vaccine received all doses. Therefore, profit estimates should be considered an upper bound.
^bAll monetary valued are reported in 2014 US dollars.
 Source: Authors' calculations.

manufacturers' share ranged from 1.3% to 2.6%. In other words, varying parameters by $\pm 10\%$ maintained a social value of at least \$37,172 per child, with at least 97% of the value retained as consumer surplus. In addition, varying the value of a QALY from \$50,000 to \$250,000 led to social value ranging from \$61 billion to \$308 billion, and varying the discount rate from 0% to 6% led to social value ranging from \$447 billion to \$107 billion. Subtracting parents' time cost led to a social value of \$182 billion and manufacture share of 1.8%.

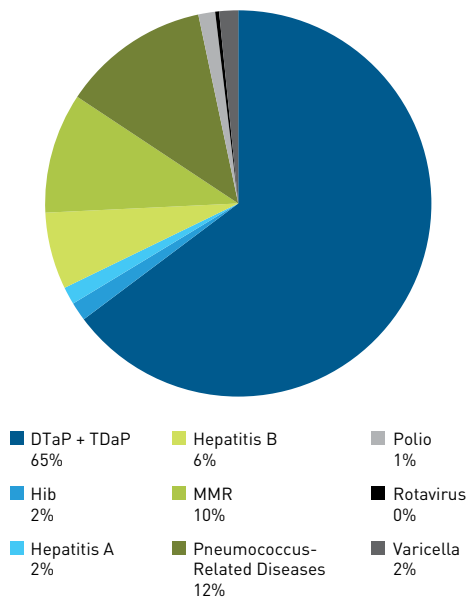
DISCUSSION

Our estimates suggest that routine childhood vaccination produces a large social value. In particular, we found that vaccination will save 1.2 million QALYs among children born in the United States in 2009, relative to a counterfactual of no vaccination. Vaccines treating common diseases, such as DTaP/Tdap, pneumococcus, and MMR, generate a particularly large share of the health benefits.

Childhood illness is often transitory, but many childhood diseases have nontrivial fatality rates, and a death in childhood costs many years of healthy life. Therefore, it is not surprising that the bulk of these health gains (88%) stems from reduced mortality, with the remainder (12%) from reduced morbidity. Valuing each life-year at \$150,000 and subtracting the production costs of vaccines, we found that vaccination of the 2009 birth cohort generated \$184 billion in social value, or \$45,000 per child. Of this, \$3.4 billion (2%) accrues to manufacturers in the form of profits, while \$180.7 billion (98%) is retained by the rest of society. Sensitivity analysis showed that the large social value and large share retained by society are robust to a wide range of plausible parameters.

The 2% manufacturers' share of social value we found is smaller than that found in similar analyses of other health interventions. The manufacturers' share of social value was between 5% to 24% in HIV/AIDS, chronic myeloid leukemia, and heart disease.^{20,21,23} The distribution of gains between manufacturers and the rest of society is determined by the cost of the intervention and the health gains it produces. Health gains will generally be larger in the context of diseases that are prevalent or take life early. Therefore, it is not surprising that childhood vaccines come out favorably in these comparisons, as they are among the most cost-effective health interventions⁴² and they preserve the health of children, who, in the absence of a devastating childhood illness, typically go on to lead a long, healthy life. To put the health results in context, in other industries, the producers' share of total social value has ranged from 4% for minivans⁴³ to 24% for broadband Internet.⁴⁴

FIGURE 1. Share of Social Value Due to Each Vaccine^{a,b}



Total Social Value: \$184 billion

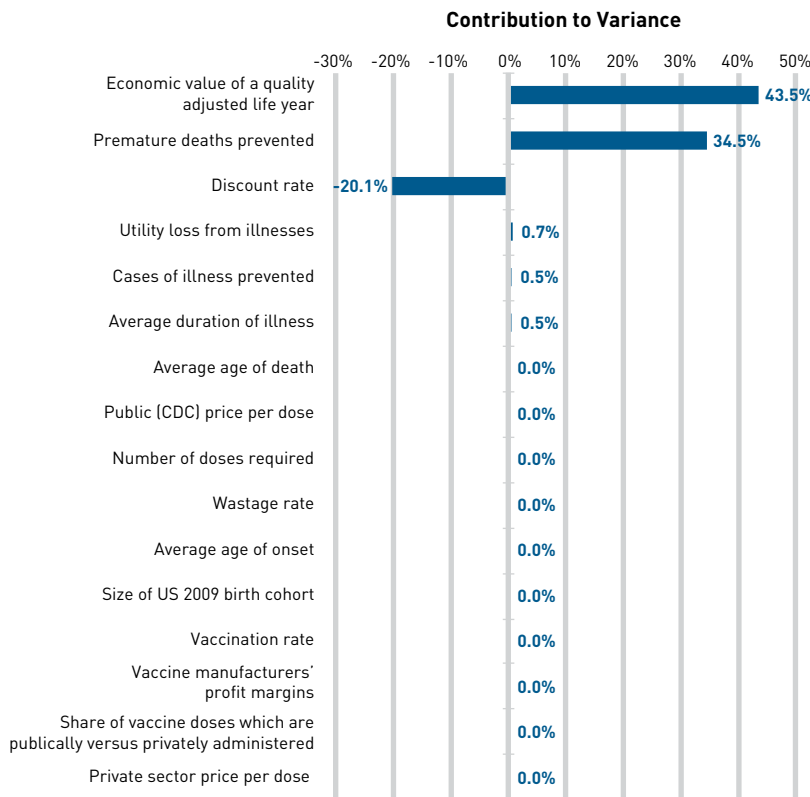
DTaP /TDaP indicates diphtheria, tetanus, and [acellular] pertussis; Hib, haemophilus influenza type b; MMR, measles, mumps, rubella, and congenital rubella syndrome.

^aSocial value is defined as: 1) the economic value of the health effects of vaccination net of the cost to consumers to obtain the vaccines, plus 2) manufacturers' profits from vaccines.

^bProfits comprise 2% of the value while consumers' health gains comprise 98%.

Source: Authors' calculations.

FIGURE 2. Results of Sensitivity Analysis (tornado chart)^a



^aAll parameters were varied ± 10%, with 1 exception: vaccination rate was varied ± 5% so as to avoid vaccination rates exceeding 100%.

Source: Authors' calculations.

The fact that 98% of the social value from existing childhood vaccines goes to children and their families is good news for access to current vaccines; however, it has longer-term implications for innovation. A 2% share of value suggests relatively weak incentives for the development of new and improved vaccines, relative to the incentives to develop cancer drugs, cholesterol-lowering drugs, or broadband Internet. However, there is debate in the literature about the exact manufacturer share of surplus required to optimally incentivize innovation, and therefore, although this study informs the debate, it does not determine optimal vaccine pricing.^{45,46}

Limitations

Because the model relies on inputs from the literature, it is limited by their availability and quality. When exact parameters were not available, conservative assumptions were made. For example, costs and profits were overestimated by assuming children who receive 1 dose of a vaccine receive all subsequent doses, thus underestimating social value and overestimating manufacturers' share. In cases in which illness is usually short and mild but can be severe and long-lasting (eg, polio), we assumed a short and mild case in

our utility calculations. In calculating profit margins, we assumed the companywide profit margin applied to a given vaccine, although vaccines may comprise a less profitable division of pharmaceutical firms.⁴⁷ We also used gross margin, which does not take R&D and marketing costs into account, rather than net margin, so that we could consider the social value as the return on society's investment in developing the vaccine.

Additionally, while the 2009 birth cohort was selected for this analysis due to the availability of data on the health effects of vaccination,²⁴ it has the drawback of including in the analysis a year of shortage of the Hib vaccine.⁴⁸ However, given the scale of the findings of this study, this consideration likely had minimal impact.

We present results at the aggregate and vaccine levels, although comparison across vaccines is imperfect. In general, prices will be higher at launch and lower after entry by competitors; however, for the childhood vaccination schedule as a whole, these lifecycle factors will tend to balance out, with little effect on our aggregate estimates.

Typical valuations of vaccines, including cost-effectiveness analyses, only partially capture their full social value,^{49,50} and this study, too, is not comprehensive. For example, this paper does not consider caregiver utility or the costs of persistent disabilities due to vaccine-preventable illnesses. In addition, it does not explicitly consider herd immunity. Herd immunity is simultaneously a large source of social value as it prevents the spread of costly illnesses for payers and society, but it is also a likely reason that some parents eschew vaccination. These dynamics should be further explored in future research.

Beyond benefiting society as a whole, public policies encouraging vaccination have value for payers in particular. Without a vaccination requirement, there is diminished incentive to vaccinate beneficiaries. There is frequent turnover in health plans and vaccinated members may leave a plan within a few years, whereas new members may come from plans with lower vaccination rates. With strong vaccination policies, even if plans lose members the plan has vaccinated, they are likely to gain members that are also vaccinated, so the risk due to turnover is reduced.

CONCLUSIONS

The childhood vaccination schedule has large benefits on population health, saving an estimated 1.2 million QALYs, and generating over

\$184 billion in social value, or \$45,000 per child. The high social value is corroborated by the CDC³⁷ and the American Academy of Pediatrics, both of which recommend routine childhood vaccination.⁵¹ Of this social value, \$3.4 billion (2%) accrues to manufacturers, while 180.7 billion (98%) is retained by the rest of society. While a small manufacturers' share may facilitate access to vaccines in the short term, it also has implications for the incentive to develop new and improved vaccines to provide further health gains in the future. ■

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vaccination, n_i is the average duration of illness i , and d_i is the average decrement to utility due to illness i .

For example, if Disease X involves 1 month with a utility of 0.6 (where a utility of 0 represents death and 1 represents perfect health), then avoiding a case of that disease would save $(1/12) \times (1 - 0.6) = 0.033$ QALYs. Those QALYs would then need to be discounted to reflect how far into the child's life the disease would have occurred, with immediate morbidity benefits valued more highly than distant ones.

Next, mortality reductions were calculated as follows:

$$\Delta h_{s_i} = h_{s_i} \times \sum_{t=h_i}^{e_i} \left(\frac{1}{1+r} \right)^t \times u_t$$

Here h_{s_i} is the number of premature deaths prevented due to vaccination against disease i , h_i is the average age of death from disease i , e_i is the life expectancy of an individual in the study cohort conditional on surviving to the average age at which death from disease i occurs (from the Human Mortality Database),²⁹ and u_t is the average utility for an individual of age t .

QALYs gained due to vaccination against each disease were valued at the standard economic value of a QALY taken from the literature. Economists value a statistical life year (or QALY) using various techniques, including survey-based methods such as conjoint analysis or contingent valuation, and revealed preference methods which measure how individuals trade financial gain for mortality risk in the real world setting.³⁰⁻³² (For example, a job which requires a greater risk of death due to its safety conditions, such as mining, will typically require a wage premium compared to a similar job in safer conditions.) The value of a statistical life year represents the value that an individual implicitly places on living an additional year. It incorporates the value of both leisure and working time and is net of the costs associated with living an additional year (including healthcare costs).

Once the QALYs gained in each disease were obtained, we summed across diseases to obtain the total value of net health effects to the study cohort from the routine pediatric vaccination schedule. The formula is as follows:

$$\Delta health_value = \sum_{i=1}^{14} \Delta h_{s_i} \times value$$

Here $\Delta health_value$ represents the economic value of the net health benefits of pediatric vaccination schedule, compared to no vaccination; and $value$ represents the economic value of a QALY.

Step 2: Estimate Manufacturers' Profits

To estimate manufacturers' profits for vaccines, we multiplied their revenues by a profit margin. Revenues were estimated as a vaccine's price multiplied by the purchased quantity. The purchased quantity depends on the number of children vaccinated, as well as the amount of additional vaccines that must be produced due to wastage (ie, 5%).³³ Mathematically, this is expressed as follows:

$$profit_i = price_i \times margin \times children_vaccinated_i \times (1 + wastage)$$

Here $profit_i$ represents the profit manufacturers earn on the vaccine against disease i , $price_i$ represents the average price of vaccine i , $margin$ represents the average profit margin vaccine manufacturers earn, $children_vaccinated_i$ is the number of children in the study cohort who are vaccinated against disease i , and $wastage$ is the wastage rate.

By modifying the profit equation, we can also obtain the manufacturers' revenue from vaccine i , as follows:

$$revenue_i = price_i \times children_vaccinated_i \times (1 + wastage)$$

The revenue will be relevant in Step 3, because it reflects the amount paid for consumers to obtain vaccines.

To obtain the average price of vaccine i , it is necessary to take into account the price per dose, the number of doses, and the timing of those doses, as follows:

$$price_i = \sum_{t=0}^{18} \left(\frac{1}{1+r} \right)^t \times n_doses_{i,t} \times p_dose_i$$

Here $n_doses_{i,t}$ is the number of doses of vaccine i to be administered, according to the CDC's routine vaccination schedule, in the child's t^{th} year of life, and p_dose_i is the price per dose of vaccine i . Since this study considers pediatric vaccinations, it is assumed that all doses will be administered in the first 18 years of life; therefore the summation runs from age 0 to 18. In the case that there is a window spanning multiple years during which a given dose could be administered, we assumed the dose was given in the earliest year. This will front-load

vaccination prices, and due to discounting, this will produce a conservative, higher total price estimate.

In the case that more than 1 manufacturer supplied a given vaccine, we averaged the price across the manufacturers.

Some diseases are prevented with combination vaccines. For example, measles is prevented through the measles, mumps, and rubella (or MMR) combination vaccine. If disease i could be prevented through either a mono or a combination vaccine, we used the mono price to avoid making assumptions on how the combo vaccine price should be distributed across the targeted diseases. Two vaccines, MMR and the vaccine targeting diphtheria, tetanus, and pertussis (DTaP/Tdap), were only available in combination formulations. Results for these 2 vaccines were reported at the vaccine, rather than the disease, level.

In addition, we accounted for the fact that vaccines are priced differently in the public versus private settings (ie, public providers usually obtain a discount). To do so, we weighted public and private vaccine prices by their respective shares of the market, as follows:

$$p_{dose_i} = public_share \times p_{public_dose_i} + private_share \times p_{private_dose_i}$$

Here, $public_share$ represents the share of vaccine doses administered publicly, $p_{public_dose_i}$ is the price per dose of vaccine i in the public sector, $private_share$ represents the share of vaccine doses administered privately, and $p_{private_dose_i}$ is the price per dose of vaccine i in the private sector.

We took average 2009 vaccine prices from the CDC VFC program data. This data contained estimated public and private prices. Because the VFC program posts multiple price lists per year, we averaged prices across 3 time points (early, mid, and late) during 2009.

The price per vaccine times the profit margin gave us an estimate of the manufacturer's profits from a single child who is vaccinated. To obtain total profit from the vaccine in the study cohort, we multiplied the per child profit by the number of children in the cohort who were vaccinated, which we obtained as follows:

$$children_vaccinated_i = N \times coverage_i$$

Here N is the number of children in the 2009 US birth cohort, (ie, the study cohort), and $coverage_i$ is the share of the cohort who were vaccinated against disease i . We obtained the coverage rate for each vaccine from CDC data.² Because vaccines typically consist of multiple doses, and vaccination rates vary by dose, it was conservatively assumed that the vaccination rate

was equal to that of the first dose. This assumption produced an upper bound on manufacturers' profits.

Once the profit from an individual vaccine had been estimated, total profits from the pediatric vaccination schedule were calculated by summing across the 14 targeted diseases:

$$profit = \sum_{i=1}^{14} profit_i$$

Finally, it should be noted that data on vaccine manufacturers' profits on the specific vaccines in question was not available. Therefore, company-wide profit margins were averaged across the top 5 vaccine manufacturers (Sanofi Pasteur, Merck, GlaxoSmithKline, Pfizer, and Novartis).³⁴

Step 3: Calculate Total Value and Shares of Value.

The social value of vaccines was derived from their morbidity and mortality benefits. Next we decomposed that value into the shares accruing to manufacturers versus the rest of society, as follows:

$$social_value \equiv total_surplus = producer_surplus + consumer_surplus$$

This means that the social value of vaccines is defined equal to the total surplus from vaccines, which is in turn composed of the producer surplus plus the consumer surplus. The producer surplus is simply the total profit from the pediatric vaccination schedule, as estimated in Step 2. The consumer surplus is defined as follows:

$$consumer_surplus = \Delta health_value - revenue$$

This formula was calculated using the change in health value estimated in Step 1 and the revenue from vaccines estimated in Step 2. Manufacturers' revenue represents the amount paid for consumers to access the vaccines.

As a sensitivity analysis, we also subtracted the parents' time cost to take the children to receive the vaccines. Following Whitney 2014,³⁵ we assumed that caregivers take 2 hours (\$18.19 per hour) off from work to take the child for vaccination and caregiver's travel cost was \$23.45. The costs were inflated to 2014 dollars. We took into account that multiple vaccines may be given in the same visit according to the recommended vaccination schedule.

Once the social value had been defined, manufacturer profits and consumer surplus were compared to the total value of vaccines, as follows:

$$\text{manufacturer_share} = \frac{\text{producer_surplus}}{\text{total_surplus}} = \frac{\text{profit}}{\text{social_value}}$$

$$\text{consumer_share} = \frac{\text{consumer_surplus}}{\text{total_surplus}} = \frac{\text{consumer_surplus}}{\text{social_value}}$$

That is the manufacturers' share of total value is equal to the producer surplus divided by the total surplus, or equivalently, to the manufacturers' profit divided by the total social value of vaccines. Similarly, the consumers' share of the total value is equal to the consumer surplus divided by the total surplus, or equivalently, to the consumer surplus divided by the total social value of vaccines.

These calculations were performed for each of the 14 studied diseases and for the entire pediatric vaccination schedule.

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eAppendix Table 1. Disease-Specific Morbidity and Morbidity Inputs

	Cases Of Illness Prevented		Premature Deaths Prevented (Net Of Adverse Events)		Average Age Of Onset (Year) ^a		Average Age Of Death (Year) ^a		Average Duration Of Illness (Years)		Utility Loss From Illness		Vaccination Rate	
	Value	Source	Value	Source	Value	Source	Value	Source	Value	Source	Value	Source	Value	Source
Congenital Rubella Syndrome	632	(1)	70	(1)	0.00	(2)	0.04 ^b	(3)	78.600 ^e	(4)	0.35 ^d	(5)	89.7%	(6)
Diphtheria	275,028	(1)	27,503	(1)	7.00	(7)	2.50	(7)	0.027	(2)	0.23 ^e	(8)	94.7%	(6)
Hib	19,606	(1)	741	(1)	0.75	(7)	2.50	(9)	0.027	(10)	0.62	(8)	93.0%	(6)
Hepatitis A	153,164	(1)	36	(1)	5.00	(11)	10.00	(7)	0.333	(12)	0.40	(13)	76.6%	(6)
Hepatitis B	239,993	(1)	3,514	(1)	25.00	(7)	7.00	(14)	0.275	(15)	0.06	(16)	68.6%	(17)
Measles	3,835,825	(1)	3,106	(1)	7.00	(7)	2.50	(14)	0.040	(7)	0.15 ^e	(8)	89.7%	(6)
Mumps	2,312,275	(1)	12	(1)	5.50	(18)	5.50	(7)	0.029	(19)	0.15 ^f	(8)	89.7%	(6)
Pertussis	2,950,836	(1)	1,062	(1)	0.50	(20)	0.50	(14)	0.077	(21)	0.19	(22)	94.7%	(6)
Pneumococcus-Related Diseases	2,323,952	(1)	5,056	(1)	2.50	(7)	1.44	(18)	0.038	(23)	0.20 ^g		92.8%	(6)
Polio	67,463	(1)	800	(1)	7.00	(24)	7.00	(25)	0.010	(25)	0.37	(26)	92.8%	(6)
Rotavirus	1,582,940	(1)	19	(1)	0.88	(27)	1.56	(7)	0.014	(7)	0.22	(28)	67.3%	(6)
Rubella	1,981,066	(1)	15	(1)	7.00	(29)	7.00	(29)	0.023	(30)	0.15 ^f	(8)	89.7%	(6)
Tetanus	169	(1)	25	(1)	0.04	(31)	0.50	(14)	0.077	(7)	0.64 ^e	(8)	94.7%	(6)
Varicella	3,942,546	(1)	73	(1)	7.00	(2)	4.00	(32)	0.038	(33)	0.15 ^f	(8)	88.8%	(6)

Hib indicates haemophilus influenza type B.

^aWhen ranges were given, midpoints were used.

^bDeath was assumed to occur in the neonatal period.

^cLife time approximated using a life expectancy of 78.6 years since that is the life expectancy at birth used in the model.

^dUtility loss of 0.35 was used based on utility loss for deafness.

^eDisability weight used instead of disutility value.

^fAssumed similar to measles based on clinician's opinion.

^gUtility loss taken for symptoms of pneumococcal diseases.

eAppendix Table 2. Vaccine Prices

	Public (CDC) Price Per Dose	Private Sector Price Per Dose
DTaP	\$13.07	\$22.83
Tdap	\$31.98	\$40.84
Hib	\$10.18	\$25.57
Hepatitis A	\$13.84	\$32.38
Hepatitis B	\$14.64	\$35.36
MMR	\$18.59	\$52.80
Pneumococcus-Related Diseases	\$79.69	\$96.34
Polio	\$12.46	\$28.98
Rotavirus	\$80.32	\$98.85
Varicella	\$72.74	\$92.51

Source: VFC CDC Vaccine Price List Archives³⁴

Notes: DTaP/Tdap, diphtheria, tetanus, and (acellular) pertussis; Hib, haemophilus influenza type b; MMR, measles, mumps, rubella, and congenital rubella syndrome; VFC, Vaccines for Children.

Prices exclude the federal excise tax. The VFC program typically updates price lists multiple times per year. Prices are an average of 3 price lists (early, middle, late) from 2009, and are expressed in 2014 USD.

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