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Consequences of a Shortage and Rationing: Evidence from a Pediatric Vaccine
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ABSTRACT

Shortages and rationing are common in health care, yet we know little about the consequences. We examine an 18-month shortage of the pediatric Haemophilus Influenzae Type B (Hib) vaccine. Using insurance claims data and variation in shortage exposure across birth cohorts, we find that the shortage reduced uptake of high-value primary doses by 4 percentage points and low-value booster doses by 26 percentage points. This suggests providers largely complied with rationing recommendations. In the long-run, catch-up vaccination occurred but was incomplete: shortage-exposed cohorts were 4 percentage points less likely to have received their booster dose years later. We also find that the shortage and rationing caused provider switches, extra provider visits, and negative spillovers to other care.

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A data appendix is available at http://www.nber.org/data-appendix/w31479

1 Introduction

Drug shortages are an "urgent public health crisis," according to the American Medical Association (2020). The Food and Drug Administration (FDA) reported 41 new shortages of drugs and vaccines in 2021 and 83 shortages that continued from previous years (FDA, 2022). Addressing drug shortages is a priority among policymakers in the United States.[1] While a common policy response in the face of shortages is recommending the rationing of supply (Hantel et al., 2019), there is limited empirical evidence on the effects of such policies. Understanding these effects is important, because the welfare effects of a shortage depend not only on the effect on quantities, but also on the allocation of quantities and on patient and provider behavior.

In this article we examine the effects of a vaccine shortage and subsequent rationing on the welfare and behavior of patients. We study this question in the context of an 18-month shortage of the pediatric Haemophilus Influenzae Type B (Hib) vaccine. The Hib vaccine shortage began in December 2007 when manufacturer Merck announced it could not guarantee the sterility of its Hib vaccine and stopped production. At the time, there was only one other approved Hib vaccine maker in the U.S., Sanofi Pasteur, which supplied about half the market. Because of the shortage, the Centers for Disease Control and Prevention (CDC) recommended delaying Hib booster doses in favor of primary series doses (CDC, 2007).

Measuring the welfare effects of a shortage presents empirical challenges, but several features of the Hib vaccine market allow us to overcome these obstacles. First, in other markets it is difficult to estimate counterfactual product demand in the absence of a shortage, due to demand fluctuations, substitution across products, and, in the case of drug markets, changes in market size resulting from variation in disease incidence. The Hib vaccine, however, is recommended for all children. Thus, the market size is straightforward to calculate. Moreover, pediatric immunization rates are remarkably stable over time and other childhood vaccines are recommended to be received on a similar schedule to the Hib vaccine, providing additional information about what uptake of the Hib vaccine might have been in the absence of a shortage. Second, in other markets it is challenging to determine if rationing during a shortage is efficient, because the value of the product to each consumer is

[1] For example, in 2018 the FDA created an inter-agency Drug Shortages Task Force to study and reduce drug shortages (Food and Drug Administration, 2019). Additionally, members of Congress have introduced legislation to address drug shortages, including S.2595: the Drug Shortages Prevention and Quality Improvement Act of 2021.

unknown. For the Hib vaccine series, however, primary doses have higher marginal benefit than booster doses (Griffiths et al., 2012),[2] allowing us to see whether rationing encourages higher-value uses.

A shortage of the Hib vaccine is also important to study in its own right. The Hib vaccine is highly effective and provides protection against Hib bacterial infections, which can cause severe brain damage, nerve damage, and death. Before the Hib vaccine was available, Hib was a leading cause of childhood meningitis and pneumonia in the United States, and approximately 20,000 children had serious Hib disease and about 1,000 died annually (CDC, 2022b). After the Hib vaccine became widely used, incidence of Hib disease rapidly declined by more than 99 percent and has remained low. Notably, from 2009 to 2018 there were only 36 Hib cases in patients younger than age 5 recorded by CDC surveillance sites (Oliver, Moro, and Blain, 2020).

We first estimate the effects of the Hib shortage and rationing on vaccination uptake in the short- and long-run. This allows us to examine how well providers adhered to the CDC recommendation to delay the booster dose and whether children caught up after delayed vaccines. The CDC recommended delaying care to prioritize the higher-value primary series vaccine, assuming that delayed children would catch up. While these types of recommendations are common, there is little observational evidence on whether providers adhere to the recommendations or on the long-term consequences of delayed vaccination.

We next consider how a shortage alters care decisions by patients.[3] There are many decisions a patient could make in response to a shortage which have different costs and spillovers. A patient could wait to see a doctor until the shortage has resolved, which might delay other care that would have otherwise been given at the same visit. Alternatively, a patient could receive other recommended preventive care on schedule and arrange a later visit for the Hib vaccine, adding to crowding in the health care system and inconvenience for patients. Finally, a patient could search for a different provider who has Hib vaccine available and is willing to administer it. Seeing an additional provider—who is less familiar with the patient's history—fragments care. Fragmented care delivery has been shown in other contexts to increase health care costs and reduce quality of care (Agha, Frandsen, and Rebitzer, 2019; Agha, Ericson, and Zhao, Forthcoming).[4]

[2]The first two primary doses of the Hib vaccine have cumulative efficacy of about 92%; the booster dose provides little added efficacy (Griffiths et al., 2012).

[3]We will refer to decisions made by patients, children, infants, or parents interchangeably. In the case of pediatric care, the decisions are typically made by adults on behalf of children.

[4]Switching providers during a vaccine series can result in incomplete and inaccurate vaccine records,

Finally, we conduct provider-level analyses to explore supply-side factors that impacted the shortage. For these analyses we explore whether providers who used the Merck Hib vaccine prior to the shortage differently reduced their primary and booster doses relative to those using the Sanofi vaccine prior to the shortage. This helps us to understand supply frictions and whether compliance with the CDC recommendation was uniform. Likewise, we explore whether there were differential impacts among providers operating in *counties* where mostly Merck doses were used prior to the shortage. This would suggest localized supply issues or differential information dissemination regarding the CDC recommendation.

We conduct these analyses using commercial insurance claims data from the Merative™ MarketScan® Research Databases, 2004-2017. We compare children who were of age to receive Hib vaccine doses during the shortage period to children from earlier or later birth cohorts. The sharp timing of the shortage combined with the recommended vaccination schedule generates clear predictions about which cohorts the Hib vaccine shortage affected. Our identification strategy assumes that in the absence of the shortage, outcomes for the shortage-exposed cohorts would have been similar to outcomes for non-exposed children. We support this assumption by showing that pre- and post-shortage outcomes are stable across cohorts and by showing that other childhood vaccines recommended to be received on a similar schedule as Hib, but which were not in shortage, did not experience the same changes during the shortage period.

We also show that our results are robust to difference-in-differences specifications in which the one vaccine recommended on the *identical* schedule (pneumococcal vaccine) is used as a control for the Hib vaccine. To the extent that the shortage had negative spillover effects on the uptake of the pneumococcal vaccine, this will bias our difference-in-differences estimates towards zero.

We find evidence of broad adherence to the CDC recommendation to delay Hib booster doses and prioritize primary doses. Among shortage-exposed cohorts, there was only a 4 percentage point reduction in children receiving their primary doses, while there was a 26 percentage point reduction in children receiving their booster dose. Our results also show that following the shortage there was significant catch-up vaccination, although it was imperfect. Years after the shortage ended shortage-exposed children were fully caught up on the primary series, but remained 4 percentage points less likely to have ever received a booster dose.[5]

which can cause unnecessary health care visits and immunizations (CDC, 2017).

[5]We also conduct analyses examining the impact of the shortage on Hib incidence. In our data we

Supplemental analyses using nationally representative National Immunization Survey-Child data, 2005-2015, suggest that during the shortage Hib doses were distributed fairly equitably across the population. We find no significant differences across race/ethnicity, household income, or maternal education. We also find that the shortage had similar effects on vaccination uptake for children regardless of whether they were privately insured, supporting the external validity of our MarketScan results.

We next examine how patients altered care decisions in the face of the shortage. We show that shortage-exposed children were about 3 percentage points less likely to be up-to-date at 18 months on the vaccine recommended to be received on the same schedule as Hib (pneumococcal vaccine) and they made 0.3 more provider visits for vaccinations by age 5 than children in surrounding cohorts. These results suggest some patients delayed their preventive care visits during the shortage, while others made additional visits to receive the missed Hib dose. We also find that children in shortage-exposed cohorts were 3 percentage points more likely to switch providers during the Hib vaccine series, consistent with patients searching for new providers in order to obtain the Hib vaccine. Extrapolating these coefficient estimates to the entire population suggests that patients were delayed receiving more than 160,000 pneumococcal vaccine doses, and there were more than 1.5 million extra provider visits and more than 140,000 provider switches.

Finally, our provider-level analyses show that the depth of the shortage varied significantly across providers. We find that providers who mostly used Merck Hib vaccines prior to the shortage reduced administration of primary series doses by about 25 percentage points (relative to the number of pneumococcal vaccines they gave) in the first six months of the shortage, and by 9 percentage points in the shortage's last year. However, for providers who used mostly the Sanofi vaccine pre-shortage, we find no reduction in the number of primary series doses given during the shortage. This suggests provider-level supply constraints may have been an issue throughout the shortage. For the booster series, we find both types of providers had similar levels of compliance in terms of rationing the booster doses, but areas with more pre-shortage Merck providers reduced their booster doses more quickly at the onset of the shortage.

This article builds on several important literatures. First, we provide novel evidence of

observe 262 children with Hib diagnoses by age 5, with a mean cumulative incidence rate of approximately 0.7 cases per 1,000 children. Our estimated effects on Hib incidence are very small in magnitude and not statistically different from zero. However, given how rare Hib diagnoses are during our sample period, we are unable to rule out large *relative* changes in disease incidence.

the short- and long-run immunization effects of a vaccine shortage. The existing literature on the impacts of drug and vaccine shortages have primarily been surveys of doctors and pharmacists and have focused on short-run effects (Tucker et al., 2020).[6] Focusing solely on the short-run may over- (or under-) state the effects of the shortage on vaccine coverage in the population if catch-up vaccination occurs (or supply frictions persist) after the end of a shortage.

Most closely related to our work, Santibanez et al. (2012) and White, Pabst, and Cullen (2011) examine the short-term effects of the Hib vaccine shortage and find evidence that the primary and booster series quantities fell substantially at the onset of the shortage. While our findings that primary and booster doses fell during the shortage by 4 and 26 percentage points, respectively, are similar to this existing literature, we also show that substantial catch-up vaccination occurred. By the time shortage-exposed cohorts reached age 5, they were as likely to be up-to-date on the primary series, and were only 4 percentage points less likely to be up-to-date on the booster dose, relative to surrounding cohorts. Understanding these long-run impacts of a shortage on vaccination rates is important as they determine population level immunity.

We also contribute to the literature by providing the first evidence on the broader healthcare utilization effects of the Hib vaccine shortage. By showing that shortage-exposed children were 3 percentage points less likely to be up-to-date on the pneumococcal vaccine at 18 months, 3 percentage points more likely to switch providers during the Hib vaccine series, and that they made 0.3 additional vaccinations visits by age 5, we capture costs of the vaccine shortage that have previously been unexamined.[7] We are aware of no previous studies of broader healthcare utilization effects of a pediatric vaccine shortage.[8]

This article additionally expands the literature examining the demand-side of the vaccine market. Our findings on the effects of the CDC rationing recommendations are con-

[6] One quantitative study is by Alpert and Jacobson (2019), who document quantity effects for various chemotherapy drug shortages using claims data. They note that a minority of chemotherapy treatments designated as in shortage experience declines in quantities, and hypothesize that in many cases providers are able to mitigate the shortage through other means.

[7] Several other studies descriptively document the harms of vaccine shortages by surveying immunization program managers, physicians, and hospital staff (Chamberlain et al., 2012; Kaakeh et al., 2011; Kempe et al., 2010).

[8] Fitzpatrick (2022) examines the impact of anti-malarial drug shortages in Uganda. She finds evidence of patient search and changes in the composition of customers. de Janvry, Sadoulet, and Villas-Boas (2010) analyze the impact of a flu vaccination shortage at a college campus and find that providing information about the shortage actually increased uptake of the vaccine, and this increase was driven by lower-risk individuals.

sistent with evidence from Lawler (2017) and Lawler (2020) showing that, in non-shortage contexts, CDC vaccination recommendations can be effective at impacting immunization uptake.[9] Similarly, our findings complement existing evidence of important spillover effects of other vaccination shocks (Andersson et al., 2021; Carpenter and Lawler, 2019; Schaller, Schulkind, and Shapiro, 2019).

Our study also contributes to the literature showing how government policies can exacerbate or mitigate drug and vaccine shortages. Although rationing recommendations are a common policy response, existing work has primarily focused on the impacts of reimbursement rates (Ridley, Bei, and Liebman, 2016; Yurukoglu, Liebman, and Ridley, 2017), or interventions targeting manufacturers (Woodcock and Wosinska, 2013; Lee et al., 2021). Recent evidence from the COVID-19 pandemic shows that governments can be effective at rationing vaccines (Kim and Lee, 2022). More broadly, by demonstrating that providers follow CDC rationing recommendations during pediatric vaccine shortages our work also relates to the literature examining physician adherence to practice recommendations (Alalouf, Miller, and Wherry, 2019; Buchmueller and Carey, 2018).

2 Background

The Hib vaccine protects against Hib bacterial infections, which can cause severe brain damage, nerve damage, and death.[10] Prior to the approval of the Hib conjugate vaccine in 1990, approximately one in 200 children under the age of 5 developed Hib infections (Oliver, Moro, and Blain, 2020), and about one thousand children died each year as a result (CDC, 2022b). After introduction of the Hib vaccine, Hib infections fell by more than 99 percent, and nearly 90 percent of Hib cases occur among children who have not received the full vaccine series.

Before the 2007-2009 Hib vaccine shortage, there were two manufacturers serving the U.S. market —Sanofi Pasteur and Merck —and each manufacturer served about half of U.S. children.[11] The Sanofi Pasteur Hib vaccine (brand names ActHIB or TriHIBit) is a 3-dose primary series, to be administered at 2, 4, and 6 months of age. The Merck Hib vaccine

[9] Other existing work on the determinants of vaccination have considered a broad set of factors, including vaccination mandates (Carpenter and Lawler, 2019; Churchill, 2021; White, 2021), insurance coverage (Chang, 2016), information shocks (Chang, 2018), and disease incidence (Oster, 2018; Schaller, Schulkind, and Shapiro, 2019).

[10] Despite its name (Haemophilus Influenzae Type B), Hib is not a form of influenza (flu).

[11] Based on author calculations using MarketScan Data.

(brand name PedvaxHIB or Comvax) is a 2-dose primary series, to be administered at 2 and 4 months of age.[12] Following completion of the Hib primary vaccine series, a booster dose of any Hib vaccine is recommended to be received at 12-15 months of age (Table 1). Catch-up vaccination is recommended for children between the ages of 15 and 59 months who are not up-to-date. Healthy children over the age of 59 months are not recommended to receive the Hib vaccine, because the risk of Hib infection is primarily for infants (Oliver, Moro, and Blain, 2020).

The Hib vaccine is one of ten vaccines routinely recommended for infants between birth and 18 months of age. However, only the pneumococcal conjugate vaccine (PCV) has a recommended dosing schedule that fully aligns with the Hib vaccine (Table 1).[13] Prior to the shortage, infants in our sample received their first two doses of pneumococcal and Hib vaccines on the same day more than 95 percent of the time.

Table 1: Recommended Vaccine Schedule

	Age in Months		
	Hib (Merck)	Hib (Sanofi Pasteur)	Pneumococcal
First Primary Dose	2	2	2
Second Primary Dose	4	4	4
Third Primary Dose	N/A	6	6
Booster Dose	12-15	12-15	12-15

Notes: Catch-up vaccination for the Hib and pneumococcal vaccines is recommended for children between the ages of 15 and 59 months who are not up-to-date. Children are considered up-to-date on the Hib vaccine if they receive any doses after age 15 months. Healthy children over the age of 59 months are not recommended to receive the Hib or pneumococcal vaccine, even if they have not previously received any doses. Source: Centers for Disease Control and Prevention.

The Hib vaccine shortage began on December 13, 2007, when Merck suspended production of its Hib vaccines due to uncertainty about the sterility of its manufacturing equipment. On December 18, 2007, the CDC issued the recommendation that the Hib booster

[12]The CDC recommends that children receive the same vaccine type (Merck or Sanofi Pasteur) for all primary series doses, although they can be used in combination. If the Sanofi Pasteur vaccine is administered as either the first or the second dose of the primary series, a total of three doses of the Hib vaccine are needed to complete the series (CDC, 2007).

[13]We provide the full recommended vaccination schedule for children aged 0-24 months in Appendix Table A1. Two other vaccines, diphtheria-tetanus-pertussis (DTaP) and polio, are on schedules similar but not exactly matching the Hib vaccine schedule. Therefore, we do not examine them in the main text, but include robustness checks using these vaccines in Appendix Tables A10 and A11.

dose be delayed until the shortage resolved, except for high-risk groups (CDC, 2007).[14] [15] According to the CDC, the risk of deferring the booster dose was low if primary series coverage remained high, especially given the low rates of Hib disease prevalence.

Eighteen months later, on June 25, 2009, Sanofi Pasteur announced increased production of its Hib vaccines.[16] Shortly afterwards, on July 1, 2009, the CDC declared that the shortage had ended and recommended resuming administration of the Hib booster dose. The CDC also recommended "limited catch-up," meaning older children with a delayed booster dose should wait to receive it until their next routinely scheduled visit (CDC, 2009d). In September 2009, the CDC updated their advice and recommended broad catch-up, with providers actively recalling patients that were in need of a booster dose (CDC, 2009c). In the fourth quarter of 2009, Merck Hib doses once again became available and Merck returned to full supply in the first quarter of 2010 (CDC, 2010).[17]

Despite the shortage, Hib vaccine prices changed little over this period. The stability of these prices is evident in Appendix Figure A1, which plots the median per dose price observed in the MarketScan data for the leading Hib vaccines. The price stability is also evident in data reported by vaccine manufacturers to the CDC. The CDC data show that in May 2007 (before the shortage), the private sector price of the Hib vaccine from Sanofi Pasteur was $21.78. In September 2008 (during the shortage), this price was unchanged, while in April 2009 (near the shortage end), the price per dose increased only slightly to $22.83 (Centers for Disease Control and Prevention, 2023).[18] In the public sector, the effective vaccine price faced by providers and patients for the Hib vaccine is zero throughout our sample period, as the federal Vaccines for Children (VFC) program directly purchases vaccine doses and supplies them to eligible providers.[19] These doses are then adminis-

[14] Children at high risk for Hib were those with "asplenia, sickle cell disease, human immunodeficiency virus infection and certain other immunodeficiency syndromes, and malignant neoplasms" and American Indian/Alaska Natives (CDC, 2007).

[15] Based on our reading of CDC materials about the shortage and subsequent rationing (for example, Centers for Disease Control and Prevention (2007), Centers for Disease Control and Prevention (2009a)) and state Department of Health "Dear Provider" letters (for example, New York State Department of Health (2008), California Vaccines For Children Program (2008)), there are no penalties for physicians who do not follow the rationing recommendation.

[16] This included the introduction of the new Sanofi Pasteur Pentacel vaccine (combination vaccine containing DTaP, polio, and Hib) which was introduced in June 2008.

[17] Also contributing to the end of the shortage, in October 2009 GlaxoSmithKline began shipping the monovalent Hib conjugate vaccine Hiberix which had previously only been available outside the U.S. (CDC, 2007).

[18] The reported private sector price for the Merck Hib vaccine was $22.77 on each of these dates (Centers for Disease Control and Prevention, 2023).

[19] It is also the case that the price VFC paid to suppliers for the Hib vaccine was relatively unchanged

tered at no charge to Medicaid-eligible, American Indian/Alaskan Native, uninsured, or underinsured children.

3 Data

Our main data source is the commercial health insurance claims data from Merative™ MarketScan® Research Databases. To complement these analyses, we also use nationally representative data from the National Immunization Survey-Child (NIS-Child). To control for time-varying county-level characteristics, we use data from the American Community Survey and Robert Wood Johnson Foundation County Health Rankings Dataset. We provide more detail about each data source below.

3.1 MarketScan

Our primary analyses use data from Merative™ MarketScan® Research Databases for 2004 to 2017. MarketScan data are a convenience sample of patients enrolled in commercial health insurance plans.[20] These data include all patient claims, as well as basic patient demographic characteristics, such as year of birth, gender, and county of residence. Each claim includes information on billed services (captured by CPT-4 codes), date of service, patient identifiers, and provider identifiers. We identify the receipt of a vaccine dose using the recorded CPT codes.[21] Because the recommended vaccination schedule for the Hib vaccine is based on child age in months, for each child in our sample we assign month of birth as the minimum of the first date at which we observe a claim and the first month

over this period. For the Sanofi Pasteur Hib vaccine, the CDC reports VFC contract prices of $8.28, $8.64, and $8.66 per dose in May 2007, September 2008, and April 2009, respectively (Centers for Disease Control and Prevention, 2023).

[20] Although these data are based on a convenience sample, Dunn, Liebman, and Shapiro (2014) find the data to have similar age and sex distributions as nationally representative estimates for the commercial insurance market. All types of insurance coverage are included in the data (e.g., PPO, POS, HMO, and indemnity), however, the data primarily covers employer-sponsored insurance, and excludes the individual market. It is also notable that while MarketScan data covers all geographic markets, a disproportionate share of observations are from the south (around 48 percent of the sample, compared with 34 percent based on nationally representative estimates).

[21] The Merck and Sanofi Pasteur Hib vaccines have different CPT codes because the technology and recommended dosing schedules differ. The CPT codes we use to identify the Hib vaccine are: 90644, 90645, 90646, 90647, 90648, 90748, 90698, 90696, 90697, 90720, 90721, 90737. The CPT codes corresponding to the Merck Hib vaccine are 90647 and 90748.

the child appears in the enrollment file.[22] Given that employer-sponsored insurance in the United States typically only allows enrollment during a fixed period of time each calendar year unless a "qualifying event," such as a birth, occurs, there are strong incentives for parents to promptly enroll their child in an insurance plan after birth (U.S. Department of Labor, 2018).

To construct individual vaccination histories and up-to-date measures, we restrict our sample to the set of children who were continuously enrolled between 0 and 5 years of age. In order to ensure that infants first appear in our data due to birth rather than changes in plan enrollment at the household level, we only include children whose parents were enrolled for longer than the child in the child's birth year. For our preferred sample, we also exclude children for whom we never observe any vaccines,[23] as well as children living in states where the Vaccines For Children (VFC) Program provides free childhood vaccines to all children.[24] After applying these restrictions, our sample consists of 322,784 commercially-insured children born between the years of 2005 and 2010.[25]

For each child in our sample we construct binary variables indicating receipt of any Hib doses, two or more doses, and up-to-date (UTD) status for the Hib vaccine at 9, 18, and 62 months of age. These ages correspond to the key thresholds in the immunization schedule (age of primary series completion, age of booster dose completion, and age beyond which catch-up vaccination is no longer recommended), plus a three month lag. We use a three-month lag to account for measurement error in the month of birth and to capture infants that are only slightly behind schedule.[26] Vaccination up-to-date measures are constructed

[22]For 57% of children the claim-based measure and the enrollment-based measure agree on the birth month. For 91% of children these measures differ by no more than one month. We further probe the validity of this assignment algorithm by comparing the assigned birth month to the mother's observed delivery month (identified using inpatient claims) for the sub-sample of children in our data for whom we also observe claims for their mother (64% of our sample). For 92% of this sub-sample, the month of birth we have assigned is within one month of the observed date of delivery.

[23]This includes not observing any vaccines for pneumococcal, Hib, polio, rotavirus, hepatitis B, hepatitis A, or DTaP.

[24]While the federal Vaccines For Children (VFC) Program supplies states with childhood vaccines to be administered at no charge to Medicaid-eligible, American Indian/Alaskan Native, uninsured, or underinsured children, during our sample period 14 states (accounting for 10 percent of the children in our data) supplement the federal VFC program and implement a "Universal" VFC program, in which free vaccines are also provided for privately insured children (CDC, 2016). In universal VFC states, providers are not reimbursed by insurance for the vaccines and therefore have less of an incentive to file a claim. In our data, vaccination rates constructed from claims are much lower in these states and often observed prices are zero when a claim is recorded.

[25]We confirm the robustness of our results to relaxing these sample restrictions, and the corresponding tables are available on request.

[26]The fraction of children in our sample that receive vaccines one to three months behind schedule

based on the type of Hib vaccine received (Merck or Sanofi Pasteur) and the age at which each dose was received. Specifically, a child is considered up-to-date on the primary series if they received at least two Merck primary doses, or, if the Sanofi Pasteur Hib vaccine was administered for any of the primary series doses, at least 3 primary doses. To be considered up-to-date on the booster dose, the child must have received the full primary series (as defined above) plus one booster dose. Alternatively, a child is considered fully up-to-date, on both the primary and booster series, if they received at least one Hib dose after age 15 months.[27]

3.2 Plots of MarketScan data

To illustrate the dynamics of the Hib vaccine shortage, we present plots of the MarketScan data. Figure 1 displays the primary versus booster doses. Figure 2 shows the Merck versus Sanofi Pasteur doses. For the plots, we divide the number of doses of the Hib vaccine (which were short starting in December 2007) by the number of pneumococcal doses (which were not short). Pneumococcal vaccine doses are recommended to be administered at the same ages as the Hib vaccine doses, and therefore serve as a proxy for the expected number of children needing a Hib vaccine in a given month. If patients also delayed receipt of the pneumococcal vaccine as a result of the Hib shortage, these figures will understate the depth of the shortage.[28]

Figure 1 shows that during the shortage, primary doses were relatively stable while booster doses declined. For booster doses, the ratio of Hib to pneumococcal doses administered was about 1 in December 2007, falling to 0.79 in January 2008, and 0.43 in June 2008. After the shortage ended in June 2009, there was a spike in booster dose administration, with over 1.5 Hib booster doses administered per pneumococcal booster dose for the months of August 2009 to January 2010.

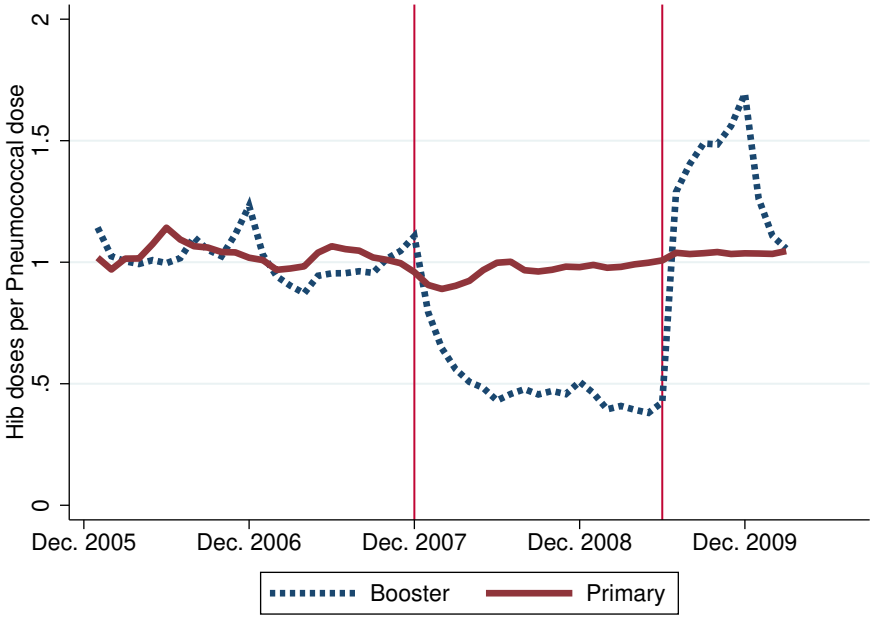
These trends suggest providers largely adhered with CDC recommendations to (1) delay

(based on our assigned month of birth) even in the absence of the shortage is high. For example, for the pneumococcal vaccine in 2006 (pre-shortage), only 41 percent of infants were up-to-date on the booster by age 15 months as recommended, whereas 60 percent were up-to-date by 18 months. Beyond 18 months the percent continues to increase but at a much slower rate: only 66 percent are up-to-date by 21 months of age.

[27] These criteria align with the CDC's Hib vaccination guidelines, which state that no further Hib doses are needed if a Hib vaccine dose is administered at age 15 months or older (Centers for Disease Control and Prevention, 2022).

[28] Appendix Figure A2 shows the number of Hib doses divided by the average number of 6-month-old children in the MarketScan data in a year. The overall patterns are consistent regardless of the denominator.

Figure 1: Ratio of Hib to Pneumococcal Doses Administered per Month, Separately for Primary and Booster Doses



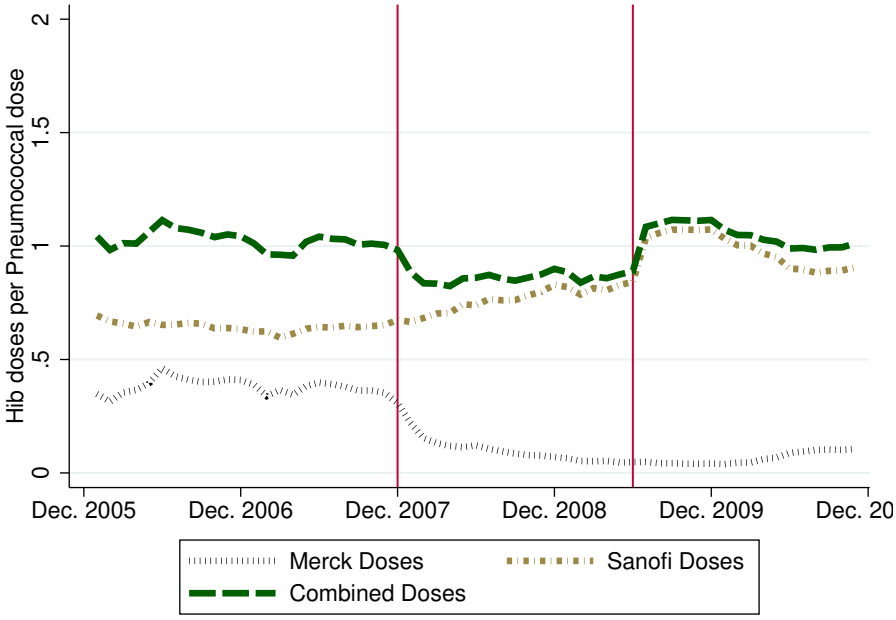
Notes: The outcome variable is Hib doses divided by pneumococcal doses in that month in the MarketScan data. Doses are split into primary series and booster doses based on a child's observed history. Primary series Merck doses count as 1.5 doses to account for Merck's two dose series.

booster doses following the start of the shortage in December 2007 and (2) administer catch-up doses following the conclusion of the shortage in June 2009. However, adherence was initially gradual, and this appears to be associated with a short-run reduction in the number of primary series doses administered at the start of the shortage.[29]

Figure 2 examines the trends in Hib vaccination separately for each manufacturer (combining primary and booster doses). The top line shows the total Hib doses per pneumococcal dose, while the lower two lines disaggregate the results by Merck and Sanofi Pasteur doses. At the beginning of the shortage there was an immediate reduction in the number of Merck doses administered, while the number of Sanofi Pasteur doses increased during the shortage period. Notably, the Merck supply was limited, but not zero, as expected

[29]The recommendation during the shortage was to continue administering the booster dose to high-risk children. Therefore, we should not expect zero Hib booster doses to be administered.

Figure 2: Ratio of Hib to Pneumococcal Doses Administered per Month, Separately by Vaccine Manufacturer



Notes: The outcome variable is Hib doses divided by pneumococcal doses in that month in the MarketScan data. Doses are split between Merck and Sanofi Pasteur. Primary series Merck doses count as 1.5 doses to account for Merck's two dose series.

given that the shelf life of a Hib vaccine is at least two years when properly stored (World Health Organization, 2000).

3.3 National Immunization Survey-Child

We supplement our primary analyses with data from the National Immunization Survey-Child (NIS-Child), 2005-2015 (CDC, 2021). The NIS-Child is a nationally representative random digit dialing survey that targets children aged 19 to 35 months, thus, our sample consists of children born between 2002 and 2014. The survey includes provider-verified vaccination histories, as well as demographic information such as insurance status, income, maternal education, and race. We provide more details about the survey in Appendix Section A2.

Unlike the MarketScan data, the NIS-Child data contain immunization information

regardless of child insurance status or provider billing decision. Thus, these data allow us to examine the effects of the shortage on vaccination rates for a nationally representative population, as well as examine heterogeneity by insurance status and other demographics. These heterogeneity analyses are important for understanding whether rationed doses were distributed equitably and the external validity of our main results.

The primary outcomes we examine in these data are indicator variables capturing whether the child has received at least one, two, or three doses of the Hib vaccine by age 18 months. These data do not distinguish between Merck or Sanofi Pasteur manufactured Hib vaccines, thus we are unable to construct more precise measures of up-to-date status, or to differentiate between primary and booster series doses. An additional limitation of the NIS-Child data is that for each child we only know year of survey and age in years at time of survey, which creates measurement error in our assignment of shortage exposure. To determine whether a given child was exposed to the shortage, we first assign each child a birth year, based on their year of interview and age at the time of interview (available in bins: 19-24 months, 25-29 months, and 30-34 months).[30] We then define those born in either 2007 or 2008 to be shortage-exposed.

3.4 Other data sources

We use measures from the American Community Survey (ACS) and the Robert Wood Johnson Foundation (RWJF) County Health Rankings Dataset as controls in some specifications. We use the ACS data from 2012 to create county-level measures of income conditional on being privately insured and under 65, to match our claims sample (Ruggles et al., 2022; University of Wisconsin Population Health Institute, 2022). We obtain demographics and various health system controls from the RWJF data. These controls include the number of primary care physicians per 100,000 (a measure of physician capacity), the share of people receiving diabetic screenings (a measure of a health system's adherence to quality guidelines), and other demographics like education and racial composition.

In addition, there are important state level policies which we incorporate into our analyses. We collected data on whether a state mandates children be up-to-date with the pneumococcal vaccine at the time of child care entry from Immunization Action Coalition

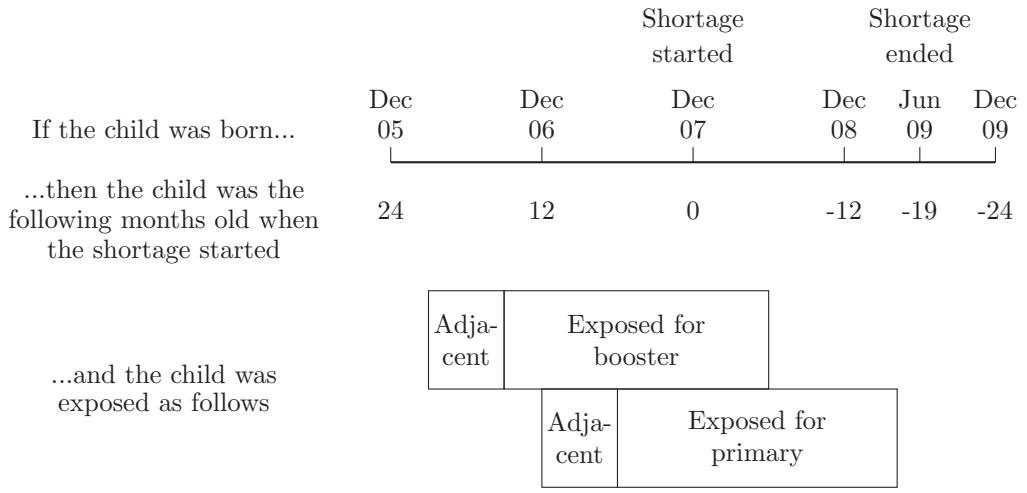
[30] For those who are interviewed when 19-24 months old, we set their birth year equal to their interview year minus one. For those 25-29 months old or 30-34 months old, we set their birth year equal to their interview year minus two.

and author's review of state statutes (IAC,2020).[31] Finally, we use data from the annual VFC Program Management Survey 2001-2010 to determine the generosity of a state's VFC program (CDC, 2015).

4 Methods

Our main source of identifying variation is differences in exposure to the shortage across birth cohorts. We define cohorts as "shortage-exposed" for a given vaccine dose if the timing of the shortage (December 2007 through June 2009) overlapped with when a child would have been of age to receive the dose. As shown in Figure 3, infants born between June 2007 and April 2009 were 2 to 6 months of age while the shortage was ongoing and therefore were exposed for the primary series. Likewise, infants born between September 2006 and June 2008 were 12 to 15 months old while the shortage was ongoing and therefore were exposed for the booster dose.

Figure 3: Mapping from Calendar Time to Cohort Time



Notes: The shortage occurred from December 2007 to June 2009. Following the recommended vaccination schedule, children born between September 2006 and June 2008 were exposed to the shortage for the booster dose. Children born between June 2007 and April 2009 were exposed to the shortage for the primary series. "Adjacent" indicates the six months preceding the exposed cohort.

[31] All states have mandates requiring children to be up-to-date on the Hib vaccine prior to daycare entry, and these mandates were adopted prior to the start of our sample period.

Because some children receive vaccine doses behind schedule even in the absence of a shortage, those born slightly before the directly exposed cohorts were partially impacted by the shortage.[32] Thus, we allow for these partially-treated cohorts to be differentially affected through the inclusion of a "shortage-adjacent" indicator that is equal to one for the cohorts that were born 6 months or less before the shortage-exposed cohorts, and is equal to zero otherwise.[33] To most cleanly identify the impact of the shortage, however, throughout the paper we focus only on the estimated impact for the shortage-exposed cohorts.

Our main regression specification is as follows:

$$\mathrm{Y}_{cm} = \beta_0 + \beta_1 \mathbb{1}(Exposed_m) + \beta_2 X_c + \epsilon_{cm} \tag{1}$$

where Y_{cm} is the outcome observed for child c born in month-year m; X_c is a vector of observable child characteristics. In our preferred specification this vector includes calendar month-of-birth fixed effects, to control for seasonality in health and vaccination uptake (Currie and Schwandt, 2013; Worsham, Woo, and Jena, 2020), an indicator variable capturing if the child was in a shortage-adjacent cohort, and Census region fixed effects.[34] $\mathbb{1}(Exposed_m)$ represents an indicator variable that is equal to one if the birth cohort was directly exposed to the shortage, and is zero otherwise. Thus, the coefficient on this variable is our treatment effect of interest, as it represents the difference in outcomes between the shortage-exposed and non-shortage exposed cohorts, net of birth month effects and other controls. Standard errors are clustered at the birth month-year level, as the availability of vaccines is the source of our treatment variation (Abadie et al., 2017). For robustness, we also report p-values from the wild cluster bootstrap procedure described in Cameron, Gelbach, and Miller (2008).

[32] For example, a child born 8 months before the shortage started would not be "exposed" for their dose scheduled at 6 months of age. However, prior to the shortage, 26 percent of children received their 6 month dose later than 8 months of age. For those children, the late dose they would have received at 8 months of age or later may not have been available during the shortage. Thus, these partially treated cohorts consist of a mixture of individuals who got the vaccine on time (before the shortage) and individuals who were behind schedule and therefore were affected by the shortage.

[33] Specifically, the "shortage-adjacent" cohorts are defined as the infants born between December 2006 and May 2007 for the primary series, and those born between March 2006 and August 2006 for the booster dose. Therefore, since our analyses focus on children born between January 2005 and December 2010, our control cohorts for the primary series are those born between January 2005 and November 2006 or born between May 2009 and December 2010. For booster dose analyses, the control cohorts are those born between January 2005 and February 2006, or between July 2008 and December 2010.

[34] In Appendix Table A2, we show that our results are robust to adding county-level demographic controls.

The identifying assumption for this model is that in the absence of the shortage, the level of the outcomes for those affected by the shortage would have been similar to those not affected by the shortage. To support this assumption we (1) show graphically that outcomes for pre-shortage and post-shortage cohorts are stable, and (2) in each regression we run a specification with a pre-shortage linear trend, to demonstrate that there were no significant linear trends in the outcomes for pre-shortage cohorts. For these pre-trend regressions we keep data only for pre-shortage cohorts and then regress each outcome (after netting out calendar month-of-birth fixed effects) on a month-year linear trend and vector of region fixed effects.[35] Formally, the regression equation is:

$$\mathrm{Y}_{cm} = \beta_0 + \beta_1 BirthMonth_m + \gamma_r + \epsilon_{cm} \tag{2}$$

where $BirthMonth_m$ is the month-year of birth and γ_r represents region fixed effects. For all analyses, we report the pre-trend regression results in the same table, in a panel below the main results.

We also provide support for the identification assumption by examining effects of the shortage on uptake of the pneumococcal, DTaP, and polio vaccines, which are administered on the same or similar schedule as the Hib vaccine but not directly affected by the shortage. These analyses provide evidence that any changes we see during the shortage for the Hib vaccine were not present (or not as large) for other vaccines, helping to rule out other concurrent factors that might explain our results. Although the Hib shortage may plausibly have spillover effects to other vaccines (e.g. if households delay well-child visits), these effects should be relatively smaller in magnitude than observed changes for the Hib vaccine.

Finally, we also implement a difference-in-differences estimation strategy where we explicitly use pneumococcal immunization rates as a control. We discuss the methodology of these analyses in detail in Appendix Section A3. Importantly, if there are spillover effects to the pneumococcal vaccine, this difference-in-differences strategy should underestimate the true effects of the shortage on uptake of the Hib vaccine.

[35] In our main specification we include calendar month fixed effects to address seasonality in health and vaccination uptake (Currie and Schwandt, 2013; Worsham, Woo, and Jena, 2020). For this truncated sample, we net out calendar month effects by running an initial regression with the full sample of the outcome on just calendar month fixed effects. We then predict the outcome net of the calendar month fixed effects, and use these predicted values for our pre-trends analysis.

5 Results

5.1 Summary statistics

For the MarketScan data, the unit of observation is an individual patient. In Table 2 we report summary statistics for the full sample, as well as separately for the cohorts exposed to the shortage for the primary series, the cohorts exposed for the booster dose, and those never exposed to the shortage. Some cohorts are exposed to the shortage for both the primary and booster doses (Figure 3), so there is overlap between the individuals in columns 2 and 3. Across all cohorts, by 9 months of age 92 percent of infants had received at least 1 Hib vaccine dose and 72 percent had received the full primary series.

We see the effect of the shortage and rationing on booster doses in the summary statistics. At 18 months, 62 percent of infants in cohorts that were never exposed to the shortage were up-to-date on the Hib booster dose, compared to only 35 percent of those exposed. These disparities are not present for the pneumococcal vaccine (Appendix Table A3). In Appendix Table A4, we present summary statistics for the county-level control variables we use. For all measures, the three different cohort groups have very similar observables.[36]

[36]In Appendix Table A5 we present the results from specifications in which observable sample characteristics are the outcome variable. A limitation of these analyses is that, since the MarketScan data has very limited person-level characteristics, these measures (with the exception of family size) are all county of residence-level measures. We note that while there are some statistically significant differences, these are generally very small in magnitude, as nearly all are less than 1% relative to the mean for that county level characteristic. Additionally, in Appendix Table A2 we show that our main results are robust to controlling for this set of time-varying child- and county-level characteristics.

Table 2: Summary Statistics

	(1) Full Sample	(2) Exposed during Primary	(3) Exposed during Booster	(4) Never Exposed
Shortage Exposed Primary	0.334	1.000	0.600	0.000
	(0.472)	(0.000)	(0.490)	(0.000)
Shortage Exposed Booster	0.306	0.550	1.000	0.000
	(0.461)	(0.498)	(0.000)	(0.000)
Any Hib Doses, 9 Months	0.917	0.911	0.918	0.920
	(0.276)	(0.285)	(0.274)	(0.271)
Hib UTD Primary, 9 Months	0.721	0.693	0.694	0.739
	(0.448)	(0.461)	(0.461)	(0.439)
Hib UTD Booster, 18 Months	0.526	0.433	0.346	0.615
	(0.499)	(0.495)	(0.476)	(0.487)
Any Hib Doses, 62 Months	0.954	0.951	0.959	0.955
	(0.210)	(0.216)	(0.199)	(0.207)
Hib UTD Primary, 62 Months	0.899	0.895	0.897	0.902
	(0.302)	(0.306)	(0.304)	(0.298)
Hib UTD Booster, 62 Months	0.793	0.797	0.766	0.803
	(0.405)	(0.402)	(0.423)	(0.398)
Observations	322784	107833	98739	175470

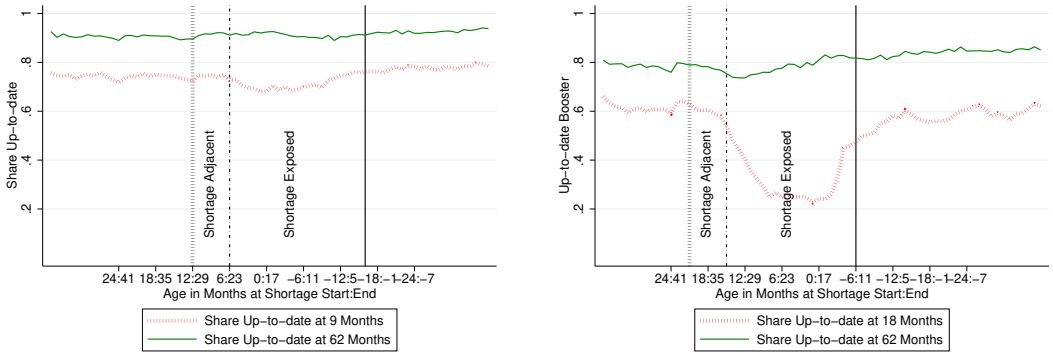
Notes: Summary statistics for outcomes and treatments for different samples using MarketScan data aggregated to the child level. The mean is listed with the standard deviation in parentheses below. Children could have been exposed during the primary series and the booster series, so columns 2-4 do not add up to the full sample of 322,784 observations. See Figure 3 for details. "UTD" indicates up-to-date.

5.2 Effect of shortage and rationing on up-to-date rates

Descriptive trends in Hib up-to-date rates are plotted in Figure 4.[37] Panel (b) shows that the shortage and rationing reduced the share of children who were up-to-date on booster doses at 18 months. Furthermore, we can see that most patients caught up with booster dose by the time they were 62 months old (at least two years after the shortage for all exposed cohorts). We see similar, though less pronounced, patterns for the primary series (Panel (a)).

[37] In Appendix Figure A3 we also present the cumulative probability of being up-to-date, separately for shortage-exposed and non-exposed cohorts.

Figure 4: Up-to-Date Rates Netting Out Calendar Month of Birth



(a) Primary Series

(b) Booster Dose

Notes: This figure presents variation in up-to-date rates for the Hib vaccine for children born in different month-years in the MarketScan data. We present results after netting out birth month effects. In Panel (a), the dotted orange line and the solid green line are share up-to-date for primary series at 9 months and 62 months, respectively. In Panel (b), the dotted orange line and the solid green line are share up-to-date for the booster dose at 18 months and 62 months, respectively.

To quantify these descriptive effects, we estimate Equation 1 and report the results in Table 3, Panel A. These results show that shortage-exposed children were 26 percentage points less likely to be up-to-date on the booster dose at age 18 months (column 5), relative to individuals in other birth cohorts. The effect for the primary doses was smaller: at 9 months of age shortage-exposed cohorts were 4.5 percentage points less likely to be fully up-to-date on the primary series (column 3) and were only 0.9 percentage points less likely to have received any Hib doses (column 1).[38]

We also demonstrate that a small fraction of patients did not catch up on missed vaccine doses. By age 62 months (at least two years after the end of the shortage for all cohorts), the exposed cohorts were still 4.4 percentage points less likely to be up-to-date on the Hib booster dose (column 6). These estimates are smaller than those at 18 months, indicating catch-up vaccination occurred. However, given that CDC recommendations for routine catch-up vaccination only extend through 59 months (thus making Hib vaccination after that age unlikely), our results imply that the Hib shortage had long-run effects on Hib vaccination coverage. Importantly, at 62 months of age we find no evidence of a

[38] For completeness we present in Appendix Table A6 estimated effects on age (in months) at receipt of each Hib dose. While a limitation of these analyses is that age is observed only among those that eventually receive the vaccine, we continue to find robust evidence that the shortage delayed receipt of Hib doses.

statistically significant reduction in uptake of the primary series doses, based on either the any dose measure (column 2) or the primary series up-to-date measure (column 4).

Table 3: The Effect of the Shortage on Hib Vaccine Up-to-Date Rates

	(1) Any doses 9 months	(2) Any doses 62 months	(3) Primary UTD 9 months	(4) Primary UTD 62 months	(5) Booster UTD 18 months	(6) Booster UTD 62 months
Panel A						
Shortage Exposed	-0.009***	-0.003	-0.045***	-0.005	-0.258***	-0.044***
	(0.002)	(0.002)	(0.006)	(0.002)	(0.022)	(0.007)
	[0.002]	[0.212]	[0.000]	[0.097]	[0.000]	[0.000]
Mean	0.92	0.95	0.72	0.90	0.53	0.79
Observations	322784	322784	322784	322784	322784	322784
Panel B						
Pre-Trend	-0.000	0.000	-0.000	-0.001*	-0.000	-0.001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)	(0.001)
	[0.867]	[0.463]	[0.214]	[0.068]	[0.858]	[0.233]
Pre-Shortage Mean	0.92	0.95	0.72	0.89	0.63	0.77
Observations	88740	88740	88740	88740	45594	45594

Notes: Each column of each panel presents coefficient estimates from a separate regression using MarketScan data aggregated to the child level. The outcome variable is given in the column header and captures receipt of a given dose of the Hib vaccine. In Panel A, the indicator variable *Shortage Exposed* captures if a child's birth cohort was of age to receive a given vaccine dose during the shortage. See Figure 3 for details. In Panel B, the reported estimate is the coefficient on a month-level time trend, estimated using only pre-shortage cohorts. Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

We conduct a number of additional analyses to test the robustness of these results. In Appendix Table A7 we show that our results are generally unchanged when we exclude post-shortage cohorts. Appendix Table A2 additionally includes controls for county-level demographics, and results are quantitatively similar to our baseline estimates. Our findings are also robust to the inclusion of state fixed effects and state level trends (available upon request).

Analyses in Appendix Figure A4 and Appendix Table A8 additionally test if the vaccine shortage impacted the incidence of Hib among shortage-exposed cohorts. While we find no

significant changes in the probability that shortage-exposed cohorts were diagnosed with Hib by age 5, we also note that given how rare the outcome is, we are unable to rule out sizable changes in *relative* terms.

In Appendix Section A5 we compute counterfactual analyses comparing the actual allocation of doses during the shortage to the best-case (full compliance) and worst-case (no compliance) scenarios. These counterfactuals suggest that the reallocation to primary doses was close to the best case scenario where physicians comply perfectly.

5.3 Pre-trends

The identifying assumption in our estimation strategy is that, in the absence of the shortage, outcomes for shortage-exposed cohorts would have been similar to those for cohorts not affected by the shortage. While Figure 4 provides graphical evidence that outcomes for the pre-shortage and post-shortage cohorts are stable, we also estimate Equation 2 to test for linear trends in the outcome variables for the pre-shortage birth cohorts. These estimates, reported in Table 3, Panel B, are consistently small in magnitude, and only one is even marginally significant. These results provide evidence in support of our assumption that, in the absence of the shortage, Hib vaccination rates across cohorts would have remained stable.

5.4 Using National Immunization Survey - Child data

In this section we use NIS-Child data to examine the effects of the shortage on a nationally representative sample of children. The NIS-Child data are helpful because the MarketScan data include only commercially-insured children and do not have individual-level measures of socio-economic status. Also, with the NIS-Child data we can examine heterogeneity in the effects of the shortage based on socio-economic status, including by race, income, maternal education, and by state VFC policy. We provide additional discussion of these data and our estimating equation in Appendix Section A2.

The results from these analyses are presented in Table 4 and show that, consistent with our main findings presented above, shortage-exposed children were significantly less likely to have received at least three doses of the Hib vaccine by 18 months of age, relative to surrounding cohorts (Panel A, column 3). Although the estimated effects are smaller in this analysis relative to our MarketScan results presented in Table 3, this is likely driven in part by the fact that in the NIS-Child there is more measurement error in the definition

of shortage-exposed, and because we lack information about whether a child is on a two or three dose primary series schedule. Appendix Table A12 shows these results are robust to additionally including individual-level controls.

Panel B-E show no evidence of heterogeneity across the socioeconomic status dimensions we consider (maternal education, household income, child race, or child insurance status).[39] These results suggests that the regulatory rationing implemented resulted in relatively equitable distribution of the Hib doses across the population. These findings also support the external validity of our MarketScan results.

In Appendix Table A13 we additionally examine heterogeneity by state VFC program generosity. The results from this analysis show that states with Universal VFC programs experienced substantially larger reductions in uptake of the booster dose during the shortage. While the cause of this heterogeneity is unclear, one hypothesis is that in Universal VFC states, governments are able to more closely regulate vaccine supply and induce compliance with the recommended rationing policy.[40] Importantly, since we omit these states from our main analyses,[41] this result suggests that, if anything, our MarketScan results likely understate the true depth of the shortage.

[39] We note, however, that the measurement error in our exposure measure for the NIS-Child attenuates our estimates and weakens our ability to detect small amounts of heterogeneity.

[40] For example, the New York VFC program limited provider VFC orders of the Hib vaccine to be 75 percent of what the practice usually ordered, and only allowed providers to order Hib vaccines once a month (New York State Department of Health, 2008).

[41] Recall that in universal VFC states recommended childhood vaccines are supplied by the government for free to all children, thus reducing the incentive for a provider to file an insurance claim and the probability that we observe vaccines in our data.

Table 4: Effect of the Shortage on Hib Vaccine Receipt, NIS-Child

	(1) 1+ Doses 18 months	(2) 2+ Doses 18 months	(3) 3+ Doses 18 months
Panel A			
Shortage Exposed	-0.000449	-0.00227	-0.101***
	(0.001)	(0.003)	(0.010)
	[0.717]	[0.588]	[0.000]
Panel B: Education			
Shortage Exposed	-0.000192	-0.00436	-0.0870***
	(0.005)	(0.006)	(0.009)
	[0.964]	[0.512]	[0.016]
Shortage Exposed × ≥12 years	0.000483	0.00427	-0.0106
	(0.006)	(0.008)	(0.008)
	[0.927]	[0.643]	[0.279]
Shortage Exposed × College Grad	-0.000985	0.00110	-0.0232
	(0.005)	(0.007)	(0.014)
	[0.866]	[0.862]	[0.164]
Panel C: Income			
Shortage Exposed	-0.00371	-0.00606**	-0.116**
	(0.002)	(0.001)	(0.026)
	[0.063]	[0.095]	[0.002]
Shortage Exposed × Above Poverty, <= $75k	0.00277	0.00706	0.0227
	(0.002)	(0.005)	(0.028)
	[0.336]	[0.265]	[0.520]
Shortage Exposed × Below Poverty	0.00663	0.00296	0.0186
	(0.005)	(0.005)	(0.019)
	[0.419]	[0.661]	[0.593]
Panel D: Race			
Shortage Exposed	-0.000371	-0.00268	-0.104***
	(0.001)	(0.002)	(0.009)
	[0.796]	[0.413]	[0.000]
Shortage Exposed × Black Only	0.00210	0.00800**	0.0141
	(0.002)	(0.002)	(0.013)
	[0.353]	[0.145]	[0.494]
Shortage Exposed × Other/Multi	-0.00259	-0.00664	0.0116
	(0.006)	(0.005)	(0.007)
	[0.670]	[0.350]	[0.186]
Panel E: Health Insurance			
Shortage Exposed	0.00352	-0.00563	-0.0954***
	(0.002)	(0.003)	(0.007)
	[0.163]	[0.201]	[0.002]
Shortage Exposed × Covered by Medicaid	-0.00422	0.00528	-0.00413
	(0.003)	(0.004)	(0.007)
	[0.242]	[0.274]	[0.625]
Shortage Exposed × Covered by Private Insurance	-0.00559	0.00365	-0.00886
	(0.003)	(0.003)	(0.009)
	[0.142]	[0.250]	[0.568]
Sample Mean	0.98	0.96	0.89
Observations	130260	130260	130260

Notes: Each column presents coefficient estimates from a separate regression using NIS-Child data at the child level. The outcome variable is an indicator for whether a child has received at least the number of Hib doses as specified in the column header. Shortage exposed is equal to one for children born in 2007 or 2008, based on our fuzzy assignment of birth years. Robust standard errors, shown in parentheses, are clustered at the birth year. Wild clustered bootstrapped p-values are reported in brackets.

5.5 Pneumococcal vaccination

We next explore whether the shortage and rationing affected other health care. The Hib vaccine shortage and rationing could cause some patients to delay their vaccination visits until the Hib vaccine was available (thus delaying the receipt of other recommended preventive care), add a provider visit once the Hib vaccine became available, or switch providers in search of the Hib vaccine.

We begin our examination of health care spillovers by looking at the effects of the Hib shortage on uptake of the pneumococcal vaccine. Recall that the CDC recommends administering the pneumococcal vaccine on the same schedule as the Hib vaccine, but the pneumococcal vaccine supply was not short during our sample period. Thus, reductions in uptake of the pneumococcal vaccine among shortage-exposed cohorts is likely due to households delaying their vaccination visit until the Hib vaccine became available.[42] Results from the estimation of Equation 1 are presented in Table 5 and show no decline in up-to-date rates for pneumococcal primary doses.[43] We do find, however, a modest 2.9 percentage point reduction in the probability of being up-to-date on the pneumococcal booster dose at 18 months of age (column 5),[44] which translates to about 160,000 children receiving a delayed pneumococcal booster dose.[45] Table 5 Panel B consistently shows precisely estimated null pre-trends in pneumococcal vaccination, providing evidence for our identifying assumption that vaccination outcome *levels* during the shortage would have remained stable in the absence of the shortage.

Overall, the small to null results for pneumococcal are suggestive of the lack of other concurrent factors which would have also affected Hib vaccination, even in the absence of the shortage. This suggests an alternative difference-in-differences identification strategy for measuring the shortage effect on Hib vaccination, where the pneumococcal vaccine is treated as the counterfactual for the Hib vaccine. Using pneumococcal as a counterfactual

[42] One potential confounder is that, around the time of the Hib shortage, some states passed mandates that require the pneumococcal vaccine prior to enrolling in child care. To address this, for these analyses we drop states that passed pneumococcal mandates between 2006 and 2008, although our results are not sensitive to this decision. For completeness, we also verify that our main Hib results are robust to not including these states. These tables are available upon request.

[43] Figure A5 in the appendix presents the analog of Figure 4 for the pneumococcal vaccine.

[44] Appendix Table A9 presents the estimated effects on age (in months) at receipt of each pneumococcal dose. In Appendix Tables A10 and A11, we provide results for a similar analysis with the DTaP and polio vaccines, which are on a similar, though not identical schedule as Hib. While they experience declines, they are much smaller in magnitude than those we see with the pneumococcal vaccine.

[45] There are about 3.75 million children born every year and the shortage lasted 1.5 years. Hence, 3.75 million $\times$ 1.5 $\times$ 0.029 $\approx$ 160,000.

will account for other factors that could affect vaccination, although it may slightly understate the effects on the Hib vaccine due to spillover effects. We discuss this identification strategy in more detail in Appendix Section A3.

In Table 6, we present results from the alternative difference-in-differences identification strategy in which the pneumococcal vaccine is explicitly treated as the counterfactual. Relative to the results from our baseline model (presented in Table 3), the difference-in-differences results are very similar in magnitude. This provides further support that the effects we estimate are the result of the shortage, as opposed to the effect of some other unobserved shock impacting vaccination uptake more broadly.

Table 5: The Effect of the Shortage on Pneumococcal Vaccine Up-to-Date Rates

	(1)	(2)	(3)	(4)	(5)	(6)
	Any doses 9 months	Any doses 62 months	Primary UTD 9 months	Primary UTD 62 months	Booster UTD 18 months	Booster UTD 62 months
Panel A						
Shortage Exposed	-0.003	-0.002	-0.005	0.012*	-0.029***	0.012
	(0.004)	(0.004)	(0.006)	(0.005)	(0.006)	(0.007)
	[0.558]	[0.710]	[0.390]	[0.022]	[0.000]	[0.090]
Mean	0.90	0.94	0.71	0.89	0.67	0.82
Observations	177351	177351	177351	177351	177351	177351
Panel B						
Pre-Trend	0.000	0.001**	0.000	0.001**	-0.001	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)
	[0.320]	[0.004]	[0.165]	[0.005]	[0.490]	[0.750]
Pre-Shortage Mean	0.87	0.91	0.69	0.86	0.62	0.74
Observations	48640	48640	48640	48640	24570	24570

Notes: Each column of each panel presents coefficient estimates from a separate regression using MarketScan data aggregated to the child level; the outcome variable is given in the column header and measures receipt of a given dose of the pneumococcal vaccine (which was not in shortage). In Panel A, the indicator variable *Shortage Exposed* captures if a child's birth cohort was of age to receive a given vaccine dose during the shortage. See Figure 3 for details. In Panel B, the reported estimate is the coefficient on a month-level time trend, estimated using only pre-shortage cohorts. Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets. For this analysis, we drop states that implemented pneumococcal mandates between 2006 and 2008.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 6: Difference-in-Differences Estimates of the Effect of the Shortage on Hib Up-to-Date Rates

	(1) Any doses 9 months	(2) Any doses 62 months	(3) Primary UTD 9 months	(4) Primary UTD 62 months	(5) Booster UTD 18 months	(6) Booster UTD 62 months
Shortage Exposed × 1(Hib)	-0.00392	0.00207	-0.0491***	-0.0183***	-0.228***	-0.0639***
	(0.007)	(0.006)	(0.005)	(0.005)	(0.026)	(0.006)
	[0.575]	[0.754]	[0.000]	[0.000]	[0.000]	[0.000]
Sample Mean	0.91	0.95	0.72	0.89	0.60	0.80
Observations	354702	354702	354702	354702	354702	354702

Notes: Each column of each panel presents coefficient estimates from a separate regression using MarketScan data aggregated to the child-vaccine level; the outcome variable is given in the column header and measures receipt of a given vaccine dose. All specifications include vaccine type (Hib or pneumococcal), birth cohort, and census region fixed effects. Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets. For this analysis, we drop states that implemented pneumococcal mandates between 2006 and 2008.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

5.6 Effects on number of visits

We next consider whether shortage-exposed children made additional doctors visits for vaccination. If patients are unable to receive a Hib vaccine dose during their routine preventive care visit due to the shortage, then they might need to return to their providers for additional visits. Additional visits can require copays, travel time, and hassle for patients, while increasing gridlock for providers.

Our measure of vaccination visits is defined as the number of observed visits where the infant received at least one dose of a childhood vaccine (Hib, pneumococcal, hepatitis A, DTaP, or polio).[46] We count visits with non-Hib vaccines in our measure because delayed Hib doses might be given during later routine vaccination visits, in which case the effect on congestion and hassle costs would be minimal. For this analysis, we define infants as shortage-exposed if they were of age to receive the Hib booster dose during the shortage, as these were the cohorts that experienced the largest changes in vaccination. We also limit our sample to those who are up-to-date on the pneumococcal and Hib booster at 62 months of age, to avoid attenuating our results by including children who never returned to receive delayed doses.

Table 7 presents evidence of the effect of the shortage on the number of vaccination visits; Figure A6 in the appendix presents the associated descriptive trends. These results show that, on average, shortage-exposed patients made 0.27 additional vaccination visits (Panel A, column 1), relative to non-exposed cohorts. This corresponds to roughly 1.5 million additional visits. Moreover, the results in column 2, in which the sample is restricted to children whose provider primarily used the Sanofi Pasteur vaccine prior to the shortage, demonstrates this increase in vaccination visits was not driven by individuals who would have received the 2-dose Merck primary vaccine series in the absence of the shortage, but now must receive the 3-dose Sanofi Pasteur vaccine series.

[46] When constructing this outcome we do not count doses of rotavirus, MMR, varicella, or hepatitis B vaccines, as these were either newly introduced or they experienced changes in the recommended schedule during our sample period.

Table 7: Effect of the Shortage on the Number of Visits by 62 Months

	(1) All Providers	(2) Provider Used Mostly Sanofi
Panel A		
Shortage Exposed	0.273***	0.282***
	(0.018)	(0.022)
	[0.000]	[0.000]
Mean	7.11	7.11
Observations	111741	60910
Panel B		
Pre-Trend	0.001	-0.000
	(0.002)	(0.003)
	[0.747]	[0.947]
Pre-Shortage Mean	6.93	6.93
Observations	17118	9756

Notes: Each column of each panel presents coefficient estimates from a separate regression using MarketScan data aggregated to the child level. The outcome variable is the number of vaccine visits a child has at 62 months old, conditional on being up-to-date on the Hib and pneumococcal vaccine. In Panel A, the indicator variable *Shortage Exposed* captures if a child's birth cohort was of age to receive a given vaccine dose during the shortage. See Figure 3 for details. In Panel B, the reported estimate is the coefficient on a month-level time trend, estimated using only pre-shortage cohorts. Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

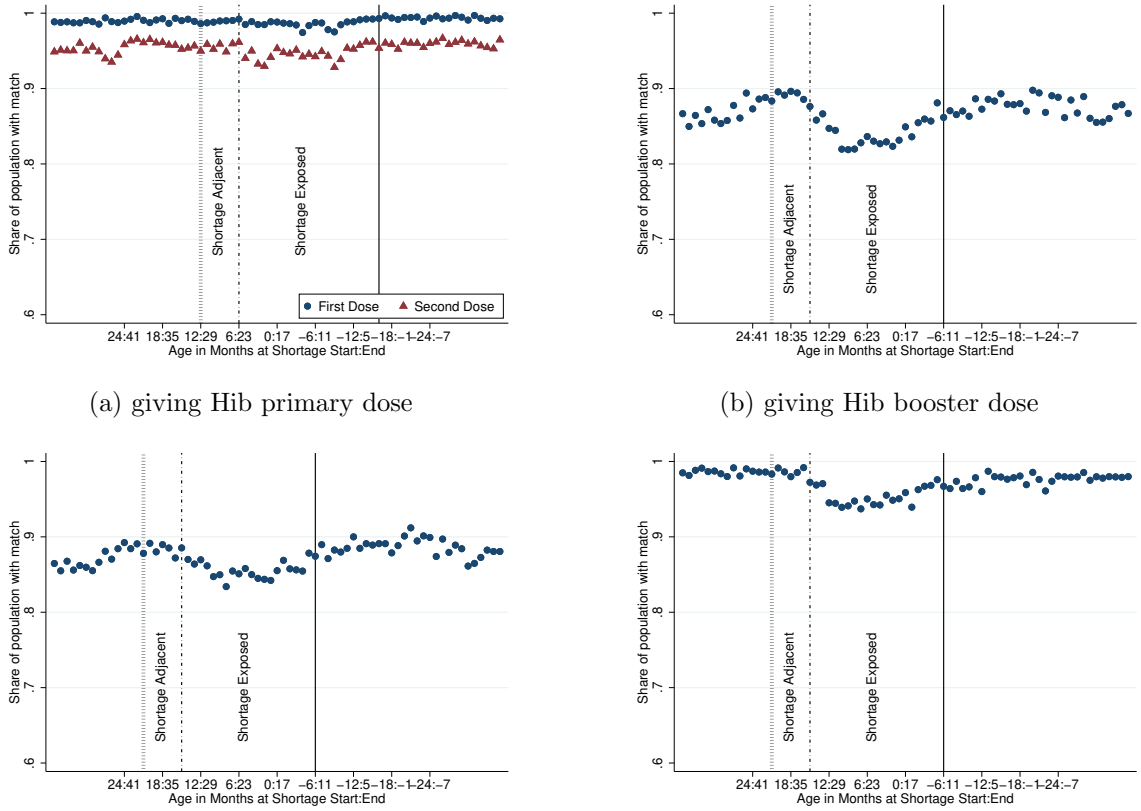
5.7 Effects on continuity of care

We next examine whether shortage-exposed patients differentially switched providers. Our primary measures of patient switching of providers are a series of indicator variables that capture if the provider that gave the infant their first *pneumococcal* vaccine dose was the same as the provider that gave that infant a subsequent vaccine dose. For each specification, the sample is limited to the set of patients who received both doses of interest, and had a valid provider identifier for both doses.

Results are presented in Figure 5 and Table 8. Across all doses considered, being in the shortage-exposed cohort reduces the probability that a patient sees the same provider for the index pneumococcal dose and for a given Hib dose. Prior to the shortage 99% of

first Hib doses are given by the same provider as the first pneumococcal dose; this is 0.5 percentage points lower for individuals in shortage-exposed cohorts (blue circles in top left of Figure 5 and Column 1 of Table 8). Reductions are larger for the booster doses of both the pneumococcal and Hib vaccine. On average, 87 percent of the pre-shortage cohort received both the pneumococcal and Hib booster doses from the same provider who administered the index pneumococcal dose. For the shortage-exposed cohorts the probability of receiving the booster dose from the same provider is 3.2 percentage points lower for Hib and 2.6 percentage points lower for the pneumococcal vaccine. In percentage terms, this is a 25 percent increase in the amount of switching for the Hib vaccine, as only 13 percent of children were switching providers before the shortage.

Figure 5: Probability That a Child Saw the Same Provider for the First Pneumococcal Dose and Later Doses



(a) giving Hib primary dose

(b) giving Hib booster dose

(c) giving pneumo. booster dose

(d) giving Hib booster dose, conditional

Notes: This figure presents variation in whether the provider who gave a child their first pneumococcal vaccine also gave the vaccine referenced in the caption or legend. Panel d is conditional on booster pneumococcal provider matching the first dose provider.

To identify the extent to which these were "one-off" switches in search of the Hib vaccine, we also look at whether the Hib booster dose was given by the same provider as the first pneumococcal dose, conditional on the pneumococcal booster dose being given by the first pneumococcal provider. This analysis shows that, among individuals that saw the same provider for their first and booster pneumococcal doses, there was a 2.5 percentage point decline in the probability of seeing that same provider for their Hib booster dose for the shortage exposed cohorts (Table 8, column 5).

Table 8: Effect of the Shortage on the Probability That a Child Saw the Same Provider for the First Pneumococcal Dose and Later Doses

	(1)	(2)	(3)	(4)	(5)
	1st Hib	2nd Hib	Hib Booster	Pneumo Booster	Hib Booster Conditional on Pneumo
Panel A					
Shortage Exposed	-0.005***	-0.010***	-0.032***	-0.026***	-0.025***
	(0.001)	(0.002)	(0.004)	(0.003)	(0.003)
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Mean	0.99	0.95	0.87	0.87	0.97
Observations	143739	134389	92842	101359	74770
Panel B					
Pre-Trend	0.0001*	0.0007***	0.0028***	0.0026***	0.0003*
	(0.0001)	(0.0001)	(0.0005)	(0.0004)	(0.0001)
	[0.0290]	[0.0000]	[0.0060]	[0.0090]	[0.0040]
Pre-Shortage Mean	0.99	0.96	0.87	0.87	0.99
Observations	48143	44590	15364	15436	11476

Notes: Each column of each panel presents coefficient estimates from a separate regression using MarketScan data aggregated to the child level; the outcome variable is an indicator variable that measures whether the provider who gave a child their first pneumococcal vaccine dose also gave the vaccine dose referenced in the column header. In Panel A, the indicator variable *Shortage Exposed* captures if a child's birth cohort was of age to receive a given vaccine dose during the shortage. See Figure 3 for details. In Panel B, the reported estimate is the coefficient on a month-level time trend, estimated using only pre-shortage cohorts. Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

We also test for linear pre-trends in the probability that a child saw the same provider for their index pneumococcal dose and for subsequent vaccine doses (Table 8, Panel B). Although these estimates are significant, they are actually *positive*, suggesting that the significant reductions in continuity of care that we find as a result of the shortage may actually underestimate the true impact.

5.8 Provider-Level Analyses

In our final set of analyses we characterize supply-side factors influencing the shortage's depth. For these analyses, we compare provider-level Hib vaccination rates during

the shortage to their rates during the two prior years. Motivated by Figure 1, we allow for different effects in the first two quarters (six months) of the shortage versus the remaining shortage period (quarters 3 through 6 of the shortage). We also allow the depth of the shortage to vary based on two pre-shortage provider characteristics: percent of Hib vaccines administered by the provider that were manufactured by Merck and percent of Hib vaccines administered in the provider's county of practice that were manufactured by Merck (omitting that provider's own doses).[47]

We approximate each provider's Hib vaccination rate by dividing the number of Hib doses by the number of pneumococcal vaccine doses the provider administered over the same time period. Although we document in Section 5.5 that the Hib shortage had modest negative spillover effects to uptake of the pneumococcal vaccine, those effects occurred only for the booster dose. Thus, for the provider-level booster dose analyses, we view our estimates as a lower bound on the true reduction in Hib immunization rates. See Appendix A4 for more details on the methodology for these analyses.

Results from the provider-level analyses are presented in Table 9. The results in column 1 show that while the shortage significantly reduced receipt of primary series doses, this reduction was concentrated in the first part of the shortage. During the first two quarters of the shortage 0.08 fewer Hib primary doses were administered per pneumococcal dose, while there is no economically or statistically significant reduction in primary doses during the remainder of the shortage. If we allow the effect of the shortage to vary based on the provider's pre-shortage Merck share (i.e. the share of pre-shortage Hib vaccines they administered that were manufactured by Merck), we find that the reduction was driven by physicians that administered primarily Merck doses prior to the shortage (column 2). Column 3 additionally allows the effects of the shortage on primary series vaccination rates to vary based on whether *other* providers in the county initially used mainly Merck or Sanofi vaccines. We find no evidence that having relatively more Merck (or Sanofi) providers in a county impacts the physician-level shortage depth for the primary series. These results suggest both that physician-level supply frictions drive the reduction in primary vaccinations and that local supply is unable to mitigate the physician-specific supply issues.

The results for the booster dose (column 4) show that the shortage resulted in larger relative reductions in vaccine administration for the booster than for the primary series doses, as expected given the CDC's recommended rationing policy. Additionally, the dy-

[47] In our data, providers tend to only use one type of Hib vaccine: prior to the shortage 77% percent of providers used at least 80% Merck vaccines or 80% Sanofi Pasteur vaccines.

namics of the reduction differ for the booster dose relative to the primary series: for the booster dose the reduction was larger in the later shortage period (0.5 fewer Hib doses per pneumococcal dose in quarters 3 through 6) relative to the first two quarters (0.34 fewer Hib doses). These dynamics suggest that providers took time to learn about and comply with the recommended rationing policy.

Results on the interactions with physician and county Merck share are qualitatively different for the booster dose than the primary dose as well. There is no evidence that the reduction in the relative number of Hib booster vaccinations significantly differed between physicians who were primarily supplied with Merck versus Sanofi vaccines prior to the shortage (column 5). This finding is consistent with the idea that observed reductions in the administration of the booster dose were driven by response to the rationing policy, as opposed to realized supply constraints. However, we do find that physicians practicing in counties with more Merck providers were relatively more likely to reduce the administration of booster doses during the first six months of the shortage (column 6), perhaps suggesting that information about the shortage and recommended rationing policy was disseminated more rapidly in areas with more Merck-supplied providers, as a higher share of physicians know directly about the issue.[48]

[48] A potential alternative explanation for this pattern of results is that in areas with more Merck providers patients are less able to switch from their original provider to get their booster dose, and therefore it is less costly for a provider to reduce the number of boosters administered (i.e. providers are less at risk of losing a patient if they refuse to administer booster doses). However, this is inconsistent with our result that mostly-Merck and mostly-Sanofi providers equally reduced booster dose administration during the first six months of the shortage.

Table 9: Provider-level results

	(1) Primary Hib Per Pneumo	(2) Primary Hib Per Pneumo	(3) Primary Hib Per Pneumo	(4) Booster Hib Per Pneumo	(5) Booster Hib Per Pneumo	(6) Booster Hib Per Pneumo
Shortage Quarters 1-2	-0.082***	0.015	0.007	-0.337***	-0.338***	-0.301***
	(0.013)	(0.015)	(0.017)	(0.020)	(0.056)	(0.060)
	[0.351]	[0.472]	[0.715]	[0.048]	[0.073]	[0.069]
Shortage Quarters 3-6	-0.009	0.024	0.015	-0.498***	-0.509***	-0.491***
	(0.012)	(0.016)	(0.017)	(0.017)	(0.026)	(0.032)
	[0.673]	[0.322]	[0.462]	[0.012]	[0.002]	[0.000]
Shortage Quarters 1-2						
× Physician Merck Share		-0.255***	-0.255***		0.004	0.024
		(0.034)	(0.033)		(0.129)	(0.126)
		[0.015]	[0.011]		[0.974]	[0.789]
Shortage Quarters 3-6						
× Physician Merck Share		-0.090**	-0.092**		0.033	0.050
		(0.029)	(0.028)		(0.048)	(0.046)
		[0.013]	[0.009]		[0.448]	[0.231]
Shortage Quarters 1-2						
× County Merck Share			0.020			-0.131**
			(0.014)			(0.039)
			[0.201]			[0.071]
Shortage Quarters 3-6						
× County Merck Share			0.026			-0.067
			(0.018)			(0.050)
			[0.197]			[0.149]
Sample Mean	0.98	0.98	0.98	0.63	0.63	0.63
Observations	44167	43157	40983	24033	23759	22637

Notes: Each column presents coefficient estimates from a separate regression using MarketScan data aggregated to the provider-quarter level. The outcome variable is the number of Hib doses given by that physician per pneumococcal dose, for either the primary or booster series. All specifications include calendar-quarter and provider fixed effects, and are weighted by the number of pneumococcal vaccines administered by the provider in a given quarter. Physician and county Merck share are constructed using pre-shortage data. Robust standard errors, shown in parentheses, are clustered at the quarter-year level. Wild clustered bootstrapped p-values are reported in brackets.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

6 Conclusions

Our analysis of the Hib vaccine shortage and rationing yields four main takeaways. First, we provide evidence that the rationing recommendation was effective. Providers mostly adhered to the rationing plan and reallocated doses from low-value booster doses to high-value primary doses. Only four percent of children fell behind on primary doses, whereas twenty-six percent fell behind on booster doses. Counterfactual analysis suggests that the reallocation to primary doses closely approximated the best-case scenario of perfect compliance by physicians (Appendix A5).

In settings with scarce resources, economists often recommend rationing using prices rather than regulatory rationing. However, price rationing typically fails to account for externalities, such as the external benefits of vaccination against an infectious disease, and can be inequitable if vaccines are allocated based on ability to pay. Our results demonstrate that regulatory rationing successfully reallocated many booster doses to higher-value primary series doses.[49] Moreover, we find no evidence of consistent differences across race/ethnicity, household income, or maternal education using the NIS-Child data.

Second, we show the long-run effects of the shortage on Hib vaccination rates. We find that many patients caught up on missed vaccine doses. However, years after the shortage resolved, shortage-exposed cohorts remained 4 percentage points less likely to have received their booster dose. Understanding these long-run effects is important given that the level of population immunity directly affects the probability of disease transmission. These results also suggest that polices such as vaccine reminder letters, which have been effective in other contexts (Hirani, 2021; Milkman et al., 2021), may be a useful policy complement to regulatory rationing.

Third, we demonstrate that while the regulatory rationing appears effective, the shortage was disruptive for the healthcare system. Our results suggest that the shortage caused delays in receipt of the pneumococcal vaccine, additional vaccination visits, and provider switching in search of available Hib doses. Thus, our paper shows how patients are negatively affected by shortages even when prices do not change, which is a point consistent with the measurement literature (Soloveichik, 2022; Diewert and Fox, 2022). Quantifying these patient responses may help policymakers understand the additional costs associated with future rationing plans.

Finally, our provider-level analyses highlight the importance of addressing supply chain

[49] We find no evidence of price changes for these vaccines during the study period (see Figure A1).

frictions. Sanofi providers experienced no measurable effect on Hib primary series vaccination during the shortage. However, providers primarily using Merck vaccines prior to the shortage gave fewer primary series doses throughout the entire shortage, with the largest effects observed during the first six months.

While these takeaways apply to many drug and vaccine shortages, we advise caution when extrapolating to other contexts, including the COVID-19 vaccine shortage. The COVID-19 vaccine shortage followed a demand shock, whereas the Hib vaccine shortage followed a supply shock. Also, the COVID-19 vaccine shortage occurred during a period of high disease burden, whereas the Hib vaccine shortage occurred during a period of low disease burden. Nevertheless, both the Hib and COVID-19 vaccine shortages demonstrate success in rationing of vaccines toward high-value uses.

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