Estimating the effect of the 2005 change in BCG policy in England: A retrospective cohort study

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**ABSTRACT**

**Background**

In 2005, England changed from universal Bacillus Calmette–Guérin (BCG) vaccination of school-age children to targeted BCG vaccination of high-risk children at birth.

**Methods**

We combined notification data from the Enhanced Tuberculosis Surveillance system, with demographic data from the Labour Force Survey to construct retrospective cohorts of individuals in England relevant to both the universal, and targeted vaccination programmes between Jan 1, 2000 and Dec 31, 2010. For each cohort, we estimated incidence rates over a 5 year follow-up period and used Poisson and Negative Binomial regression models in order to estimate the impact of the change in policy on TB burden.

**Results**

We found some evidence that the change in BCG policy was associated with a 8% (95%CI -3%, 19%) increase in incidence rates in the UK born school-age population and weaker evidence of an association with a 4% (95%CI -14%, 18%) reduction in incidence rates in UK born neonates. In the non-UK born, we found evidence for an association between a reduction in incidence rates and the change in BCG policy (school-age: 26% (95%CI 12%, 39%), neonates: 38% (95%CI 12%, 56%)). We found that the change in BCG policy was associated with preventing 385 (95%CI -105, 881) cases in the study population.

**Conclusions**

The change in BCG policy was associated with reduced incidence in the study population. In the UK born, incidence rates increased in those at school-age and decreased slightly in neonates, whilst in the non-UK born incidence rates decreased in both groups.

**Keywords:**

BCG, surveillance, vaccination policy, neonatal

**Key Messages**

* There is little existing literature on impact of withdrawing universal school-age BCG vaccination and introducing high-risk neonatal BCG vaccination on TB incidence rates in the populations directly affected by the vaccination programmes.
* There was evidence that the change in policy was associated with an increase in TB incidence rates in those relevant to the universal school-age scheme, with little evidence of a decrease in incidence rates in those relevant to the high-risk neonatal vaccination scheme, and strong evidence of large decreases in incidence rates in non-UK born neonates and those at school-age. Overall the change in vaccination policy was associated with preventing a substantial number of TB cases, mainly in the non-UK born.
* These results provide an important evaluation of the direct effects of both withdrawing and implementing a BCG vaccination programme in a low incidence, high income, country and are relevant to several other countries that have made similar changes to their vaccination programmes.

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**INTRODUCTION**

In 2005 England changed its Bacillus Calmette–Guérin (BCG) vaccination policy against tuberculosis (TB) from a universal school-age programme to vaccination at birth for high-risk neonates, identified by local Tuberculosis (TB) incidence and by the parents’ and grandparents’ country of origin. This was based on evidence of reduced TB transmission,(1–3) and high effectiveness in children,(4–6) compared to evidence of variable effectiveness in adults.(7) Little work has been done to evaluate the impact of this change in vaccination policy.

Globally, several countries with low TB incidence have moved from universal vaccination, either of those at school-age or neonates, to targeted vaccination of neonates considered to at high-risk of TB.(8) In Sweden, which discontinued universal vaccination of neonates in favour of targeted vaccination of those at high risk, incidence rates in Swedish-born children increased slightly after the change in policy. (9) A study in France, which also switched from universal vaccination of neonates to targeted vaccination of those at high-risk, found that targeted vaccination of neonates may have reduced coverage in those most at risk.(10) In England, the number of notifications of TB increased from 6929 in 2004 to 8280 in 2011 but have since declined to 5137 in 2017.(1) A recent study found that this reduction may be linked to improved TB interventions.(11) Directly linking trends in TB incidence to transmission is complex because after an initial infection an individual may either develop active disease, or enter a latent stage which then may later develop into active disease. Incidence in children (0-14 years old) is a proxy of TB transmission, because any active TB disease in this population is attributable to recent transmission. Using this approach it is thought that TB transmission has been falling in England for the last 5 years, a notion supported using strain typing.(1) However, this does not take into account the change in BCG policy, which is likely to have reduced incidence rates in children.

Although the long term effects of BCG vaccination such as reducing the reactivation of latent cases and decreasing on-wards transmission are not readily detectable over short time scales the direct effects of vaccination on incidence rates can be estimated in vaccinated populations, when compared to comparable unvaccinated populations.(12) We aimed to estimate the impact of the change in BCG policy on incidence rates, in both the UK and non-UK born populations, directly affected by it.

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**METHODS**

**Data sources**

Data on all notifications from the Enhanced Tuberculosis Surveillance (ETS) system from Jan 1, 2000 to Dec 31, 2015 were obtained from Public Health England (PHE). The ETS is maintained by PHE, and collects demographic, clinical, and microbiological data on all notified cases in England. A descriptive analysis of TB epidemiology in England is published each year, which fully details data collection, cleaning, and trends in TB incidence.(1)

We obtained yearly population estimates from the April to June Labour Force Survey (LFS) for 2000-2015. The LFS is a study of the employment circumstances of the UK population, and provides the official measures of employment and unemployment in the UK, but also captures whether individuals were UK or non-UK-born. Reporting practices have changed with time so the appropriate variables for age, country of origin, country of birth, and survey weight were extracted from each yearly extract, standardised, and combined into a single data-set.

**Retrospective cohorts**

Cases were identified as being relevant to either the universal programme or the targeted programme, between 2000 and 2010, based on date of birth and date of TB notification. For the universal programme we defined relevant cases as individuals aged 14 between 2000-2010, who were notified with TB whilst aged 14-19 years old. Similarly, for the targeted programme we defined relevant cases as individuals born between 2000-2010, who were notified with TB whilst aged 0-5 years old. Cases that were relevant to the universal programme were defined to be eligible for it if they were aged 14 between 2000-2004, and otherwise were defined to have not been eligible. Similarly, cases that were relevant to the targeted programme were defined to be eligible for it if they had been born between 2005-2010, and were defined to not eligible for it if they had been born prior to this. Cases were then stratified by UK birth status, with both non-UK born and UK born cases assumed to have been exposed to England’s vaccination policy if eligible for the relevant programme. The LFS population estimates were similarly classified; resulting in 8 population level cohorts, each with 5 years of follow up (Table 1).

Table 1: Summary of relevance and eligibility criteria for each cohort.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Cohort label | Vaccination programme | Eligible for the programme\* | Birth status | Age at study entry | Year of study entry |
| UEUK14 | Universal | Yes | UK born | 14 | 2000-2004 |
| UNEUK14 | Universal | No | UK born | 14 | 2005-2010 |
| UENUK14 | Universal | Yes | Non-UK born | 14 | 2000-2004 |
| UNENUK14 | Universal | No | Non-UK born | 14 | 2005-2010 |
| TNEUKBirth | Targeted | No | UK born | Birth | 2000-2004 |
| TEUKBirth | Targeted | Yes | UK born | Birth | 2005-2010 |
| TNENUKBirth | Targeted | No | Non-UK born | Birth | 2000-2004 |
| TENUKBirth | Targeted | Yes | Non-UK born | Birth | 2005-2010 |
| \* Eligible signifies that the cohort fit the criteria for the programme and entered the study during the time period it was in operation not that the cohort was vaccinated by the programme. | | | | | |

**Statistical methods**

We estimated incidence rates (with 95% confidence intervals) stratified by UK birth status, age, and year of notification, with the epiR package.(13) UK birth status was incomplete with some evidence of a missing not at random mechanism. We imputed the missing data using gradient boosting, with the h2o package (see supplementary information).(14) We then used descriptive analysis to describe the observed trends in age-specific incidence rates over the study period, comparing incidence rates in the study populations relevant to both vaccination programmes before and after the change in BCG policy.

We calculated Incidence Rate Ratios (IRRs) for the change in incidence rates associated with the change in BCG vaccination policy for both the UK born and non-UK born populations that were relevant to the universal programme, and for the targeted programme using a range of models. We considered the following covariates: age,(1,7) incidence rates in both the UK born and non-UK born who were not in the age group of interest,(1) and year of study entry (as a random intercept). Multiple models were considered because the precise structure and magnitude of the confounding was uncertain. We first investigated univariable Poisson models, before adding additional covariates and combinations of covariates. We also investigated a Negative Binomial model adjusting for the same set of covariates as in the best fitting Poisson model. Supplementary Table S1 outlines the details of each model included in the analysis. The models were estimated using a Bayesian approach with default weakly informative priors for the regression parameters. fitted using Markov Chain Monte Carlo fitting using brms package and STAN for all models.(15,16) Models were run until convergence (4 chains with a burn in of 10,000, and 10,000 sampled iterations each), with convergence being assessed using trace plots and the R hat diagnostic.(16) Model fit was assessed using the leave one out cross validation information criterion (LOOIC).(17) Models were then ranked by goodness of fit, using their LOOIC. The inclusion of the change in policy in the best fitting model was then tested by refitting the model excluding the change in policy and comparing the LOOIC scores. All numeric confounders were centered and scaled by their standard deviation, and age was adjusted for using single year of age categories. Once the best fitting model had been identified we estimated the number of cases prevented, from 2005 until 2015, for each vaccination programme in the study population relevant to that programme (see supplementary information). R was used for all analysis.(18)

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**RESULTS**

**Descriptive analysis**

Between Jan 1, 2000 and Dec 31, 2015 there were 114,820 notifications of TB in England, of which 93% (106765/114820) had their birth status recorded. Of notifications with a known birth status 27% (29096/106765) were UK born, in comparison to 33% (2634/8055) in cases with an imputed birth status. Trends in incidence rates varied by age group and UK birth status (see supplementary information). During the study period, there were 1729 UK born cases and 2797 non-UK born cases in individuals relevant to the universal schools scheme, and 1431 UK born cases and 238 non-UK born cases relevant to the targeted neonatal scheme, who fit our age criteria. Univariable evidence for differences between mean incidence rates before and after the change in BCG policy in the UK born was weak. In the non-UK born incidence rates were lower after the change in BCG policy in both the cohort relevant to the universal school-age scheme and the cohort relevant to the targeted neonatal scheme (Figure 1).

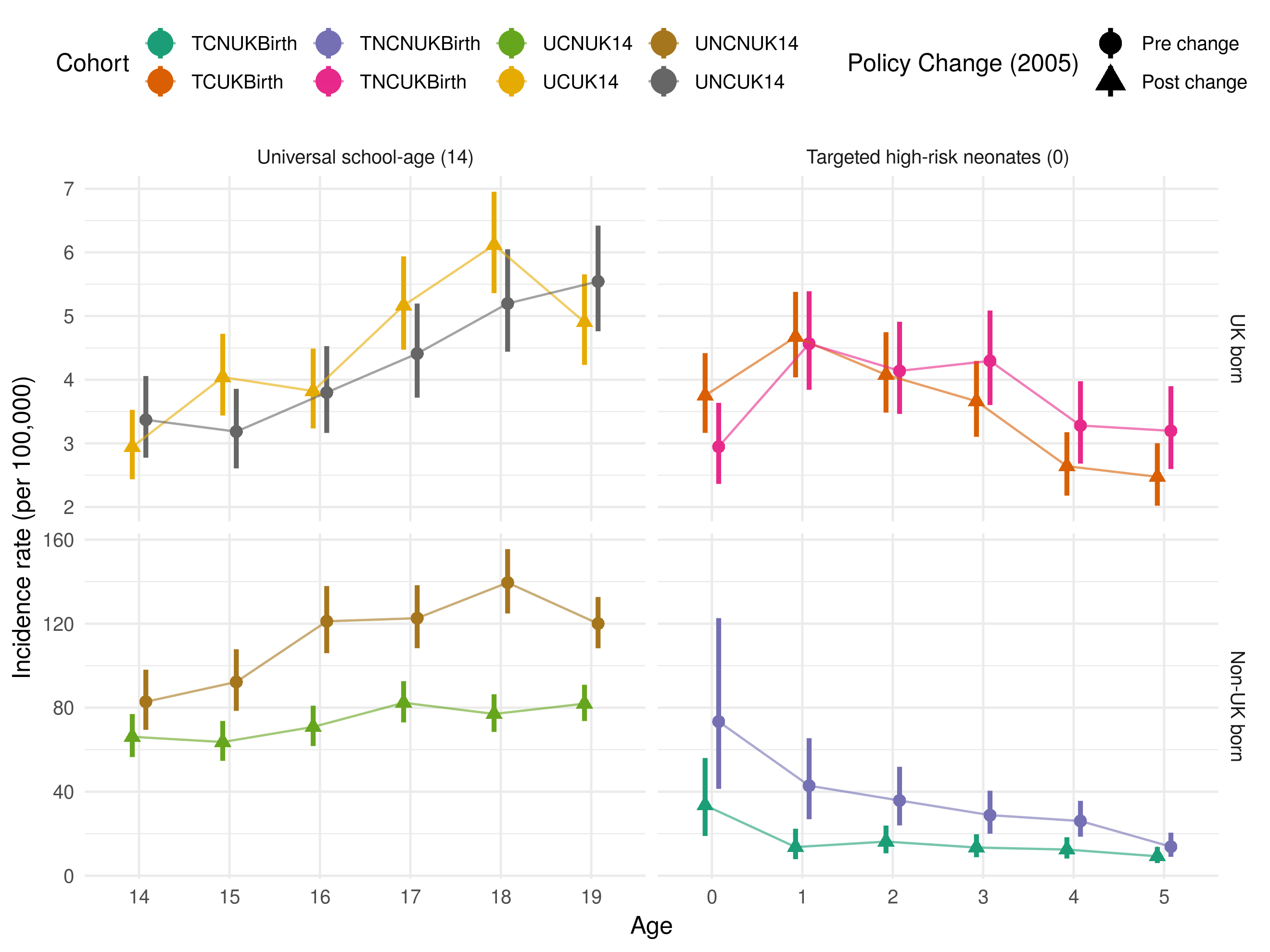


Figure 1: Mean incidence rates per 100,000 for each retrospective cohort (seeTable 1for cohort definitions), stratified by the vaccination policy.

**Direct effects of the change in policy in those relevant to the universal school-age programme**

In the UK born cohort relevant to universal vaccination there was some evidence, across all models that adjusted for age, that ending the scheme was associated with a modest increase in TB rates (Supplementary Table S2). Using the LOOIC goodness of fit criteria the best fitting model was found to be a Negative Binomial model that adjusted for the change in policy, age, and incidence rates in the UK born (Table 2). In this model there was an estimated 8% (95%CI -3%, 19%) increase in incidence rates in those at school-age, who were UK born, associated with the change in policy. There was little evidence to suggest that dropping the change in policy from this model substantially improved the quality of the fit, with an improvement in the LOOIC score of 0.52 (SE 2.63). We found that it was important to adjust for UK born incidence rates, otherwise the impact from the change in BCG vaccination policy was over-estimated.

For the comparable non-UK born cohort who were relevant to the universal vaccination there was evidence, in the best fitting model, that ending the scheme was associated with a decrease in incidence rates of 26% (95%CI 12%, 39%) (Table 2). The best fitting model was a Negative Binomial model which adjusted for the change in policy, age, incidence rates in the non-UK born, and year of eligibility as a random effect. Dropping the change in policy from this model resulted in an increase in the LOOIC of 3.02 (SE 3.52). All models that adjusted for incidence rates in the UK born or non-UK born estimated similar IRRs (Supplementary Table S3).

Table 2: Summary table of incidence rate ratios, in the UK born and non-UK born cohorts relevant to the universal school-age scheme, using the best fitting models as determined by comparison of the LOOIC (UK born: Negative binomial model adjusting with fixed effects for the change in policy, age, and incidence rates in the UK born (Model 7 (Negative Binomial)), Non-UK born: Negative binomial model with a random intercept for year of study entry, adjusting with fixed effects for the change in policy, age, and incidence rates in the non-UK born (Model 17 (Negative Binomial))). Model terms which were not included in a given cohort are indicated using a hyphen (-).

|  |  |  |
| --- | --- | --- |
| Variable | UK born\* | Non-UK born\* |
| Policy change† |  |  |
| Pre-change | *Reference* | *Reference* |
| Post-change | 1.08 (0.97, 1.19) | 0.74 (0.61, 0.88) |
| Age |  |  |
| 14 | *Reference* | *Reference* |
| 15 | 1.18 (0.98, 1.42) | 1.03 (0.87, 1.22) |
| 16 | 1.24 (1.03, 1.50) | 1.25 (1.07, 1.47) |
| 17 | 1.59 (1.33, 1.91) | 1.40 (1.19, 1.63) |
| 18 | 1.92 (1.60, 2.30) | 1.47 (1.26, 1.73) |
| 19 | 1.80 (1.49, 2.17) | 1.47 (1.24, 1.73) |
| UK born incidence rate (per standard deviation) | 1.08 (1.03, 1.14) | - |
| Non-UK born incidence rate (per standard deviation) | - | 1.11 (1.03, 1.19) |
| Year of study elibility, group level | - |  |
| Intercept (standard deviation) | - | 1.13 (1.05, 1.26) |
| Year of study elibility, individual level | - |  |
| 2000 | - | 1.10 (0.96, 1.29) |
| 2001 | - | 1.06 (0.93, 1.24) |
| 2002 | - | 1.07 (0.94, 1.25) |
| 2003 | - | 0.90 (0.76, 1.03) |
| 2004 | - | 0.89 (0.75, 1.02) |
| 2005 | - | 0.98 (0.85, 1.12) |
| 2006 | - | 1.13 (0.99, 1.33) |
| 2007 | - | 1.04 (0.91, 1.20) |
| 2008 | - | 0.96 (0.83, 1.09) |
| 2009 | - | 0.95 (0.81, 1.08) |
| 2010 | - | 0.96 (0.82, 1.11) |
| \* Incidence Rate Ratio (95% Credible Interval)  † There was an improvement in the LOOIC score of 0.52 (SE 2.63) from dropping the change in policy from the model in the UK born cohort and a -3.02 (SE 3.52) improvement in the non-UK born cohort. | | |

**Direct effects of the change in policy in those relevant to the targeted neonatal programme**

For the UK born cohort relevant to the targeted neonatal vaccination the evidence across all models was mixed with several models estimating a small decrease in incidence rates, several models estimating a small increase in incidence rates, and several models estimating little impact of the change in policy (Supplementary Table S4). All models had wide credible intervals compared to models in the UK born cohort relevant universal school-age vaccination (Supplementary Table S2). The best fitting model was a Poisson model which adjusted for the change in policy, age, UK born incidence rates, and year of study entry with a random effect (Table 3). This model estimated a 4% (95%CI -14%, 18%) decrease in incidence rates in UK born neonates associated with the change in BCG policy, although the credible intervals were wide. There was weak evidence to suggest that dropping the change in policy from this model improved the quality of the fit, with an improvement in the LOOIC score of 0.92 (SE 1.07). Models which also adjusted for non-UK born incidence rates estimated that the change in policy was associated with no change in incidence rates in the relevant cohort of neonates.

For the comparable non-UK born cohort who were relevant to the targeted neonatal vaccination programme there was evidence, across all models, that change in policy was associated with a large decrease in incidence rates. The best fitting model, which was a Negative Binomial model that adjusted for the change in policy, age, and non-UK born incidence rates, estimated that a 38% (95%CI 12%, 56%) decrease in incidence rates in non-UK born neonates was associated with the change in vaccination policy (Table 3). All models which at least adjusted for age estimated comparable effects of the change in policy (Supplementary Table S5).

Table 3: Summary table of incidence rate ratios, in the UK born and non-UK born cohorts relevant to the targeted neonatal scheme, using the best fitting models as determined by comparison of the LOOIC (UK born: Poisson model with a random intercept for year of study entry, adjusting with fixed effects for the change in policy, age, and incidence rates in the UK born (Model 16), Non-UK born: Negative binomial model adjusting with fixed effects for the change in policy, age, and incidence rates in the non-UK born (Model 8 (Negative Binomial))). Model terms which were not included in a given cohort are indicated using a hyphen (-).

|  |  |  |
| --- | --- | --- |
| Variable | UK born\* | Non-UK born\* |
| Policy change† |  |  |
| Pre-change | *Reference* | *Reference* |
| Post-change | 0.96 (0.82, 1.14) | 0.62 (0.44, 0.88) |
| Age |  |  |
| 0 | *Reference* | *Reference* |
| 1 | 1.39 (1.20, 1.61) | 0.49 (0.30, 0.83) |
| 2 | 1.24 (1.06, 1.44) | 0.49 (0.30, 0.80) |
| 3 | 1.21 (1.03, 1.41) | 0.42 (0.26, 0.68) |
| 4 | 0.90 (0.76, 1.06) | 0.41 (0.25, 0.66) |
| 5 | 0.89 (0.75, 1.06) | 0.27 (0.16, 0.45) |
| UK born incidence rate (per standard deviation) | 1.12 (1.06, 1.18) | - |
| Non-UK born incidence rate (per standard deviation) | - | 1.25 (1.04, 1.51) |
| Year of study elibility, group level |  | - |
| Intercept (standard deviation) | 1.13 (1.04, 1.26) | - |
| Year of study elibility, individual level |  | - |
| 2000 | 0.83 (0.68, 0.99) | - |
| 2001 | 0.93 (0.79, 1.07) | - |
| 2002 | 1.08 (0.95, 1.28) | - |
| 2003 | 1.07 (0.93, 1.26) | - |
| 2004 | 1.12 (0.97, 1.32) | - |
| 2005 | 1.02 (0.89, 1.17) | - |
| 2006 | 1.02 (0.89, 1.17) | - |
| 2007 | 0.97 (0.83, 1.11) | - |
| 2008 | 1.01 (0.88, 1.15) | - |
| 2009 | 1.01 (0.88, 1.16) | - |
| 2010 | 0.98 (0.85, 1.13) | - |
| \* Incidence Rate Ratio (95% Credible Interval)  † There was an improvement in the LOOIC score of 0.92 (SE 1.07) from dropping the change in policy from the model in the UK born cohort and a -3.45 (SE 4.63) improvement in the non-UK born cohort. | | |

**Magnitude of the estimated impact of the change in BCG policy**

We estimate that the change in vaccination policy was associated wit preventing 385 (95%CI -105, 881) cases from 2005 until the end of the study period in the directly impacted populations after 5 years of follow up (Table 4). The majority of the cases prevented were in the non-UK born, with cases increasing slightly overall in the UK born. This was due to cases increasing in the UK born at school-age, and decreasing in UK born neonates, although both these estimates had large credible intervals.

Table 4: Estimated number of cases prevented, from 2005 until 2015, for each vaccination programme in the study population relevant to that programme, using the best fitting model for each cohort.

|  |  |  |  |
| --- | --- | --- | --- |
| Vaccination Programme | Birth Status | Cases Prevented (95% CI\*) | Notified Cases |
| Universal school-age (14) |  | -291 (24, -571) | 2364 |
|  | UK born | 76 (188, -26) | 969 |
|  | Non-UK born | -367 (-165, -546) | 1395 |
| Targeted high-risk neonates (0) |  | 94 (-81, 310) | 906 |
|  | UK born | 30 (-95, 173) | 800 |
|  | Non-UK born | 65 (14, 137) | 106 |
| Change in Policy† |  | 385 (-105, 881) | 3270 |
|  | UK born | -46 (-284, 199) | 1769 |
|  | Non-UK born | 431 (179, 682) | 1501 |
| \*95% CI: 95% Credible Interval,  † Estimated total number of cases prevented due to the change in vaccination policy in 2005 | | | |

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**DISCUSSION**

We found some evidence that the change in BCG policy was associated with a modest increase in incidence rates in the UK born population who were relevant to the universal school-age scheme and weaker evidence of a small decrease in incidence rates in the UK born population relevant to the targeted neonatal scheme. In the non-UK born we found evidence of an association between the change in policy and a decrease in incidence rates in both those at school-age and neonates, after 5 years of follow up. Overall, we found that the change in policy was associated with preventing 385 (95%CI -105, 881) cases in the study population, from 2005 until the end of the study period, with the majority of the cases prevented in the non-UK born.

Tuberculosis is a complex disease and the BCG vaccine is known to offer imperfect protection, which has been shown to vary both spatially and with time since vaccination.(19,20) By focusing on the impact of the change in policy on the directly affected populations within a short period of time, and by employing a multi-model approach we have limited the potential impact of these issues. Our study was based on a routine observational data set (ETS), and a repeated survey (LFS) both of which may have introduced bias. Whilst the LFS is a robust data source, widely used in academic studies,(21–23) it is susceptible to sampling errors particularly in the young, and in the old, which may have biased the estimated incidence rates. However as the LFS is a well established survey it is unlikely that these biases have varied with time, therefore they should not impact our analysis as we have investigated trends in incidence rates, rather than absolute incidence rates. As the ETS system is a routine surveillance data set, some level of under-reporting is likely,(24) as is some level of missing data, for which an unknown missing not at random mechanism cannot be discounted. However, UK birth status is relatively complete (93% (106765/114820)) and we imputed missing values using a robust approach. We were unable to adjust for known demographic risk factors for TB, notably socio-economic status,(25,26) and ethnicity.(25–27) However, this confounding is likely to be mitigated by our use of multiple cohorts and our adjustment for incidence rates in the UK born and non-UK born. Finally, we have assumed that the effect we have estimated for the change in BCG policy is due to the changes in BCG vaccination policy as well as other associated changes in TB control policy, after adjusting for hypothesised confounders. However, there may be additional covariates that we have not considered which may confound this relationship.

Whilst little work has been done to assess the impact of the 2005 change in BCG vaccination several other studies have estimated the impact of changing BCG vaccination policy, although typically only from universal vaccination of neonates to targeted vaccination of high-risk neonates. A previous study in Sweden found that incidence rates in Swedish-born children increased after high-risk neonatal vaccination was implemented in place of a universal neonatal program, this corresponds with our finding that introducing neonatal vaccination had little impact on incidence rates in UK born neonates. Our results are substantially more robust as we were able to adjust for incidence rates in the general population, likely to be a key driver of incidence in the population targeted by vaccination programmes. Theoretical approaches have indicated that targeted vaccination of those at high-risk may be optimal in low incidence settings. (28) Our study extends this work by also considering the age of those given BCG vaccination, although we were unable to estimate the impact of a universal neonatal scheme as this has never been implemented nationally in England. It has previously been shown that targeted vaccination programmes may not reach those considered most at risk,(29) our findings support this view as we observed only a small decrease in incidence rates in UK born neonates after the introduction of the targeted neonatal vaccination programme. Whilst no direct estimates have been made of the impact on TB incidence rates from the change in BCG policy in England a previous study did estimate BCG coverage at 68% (95%CI 65%, 71%) amongst those eligible for the targeted neonatal vaccination programme. (30) This coverage estimate would indicate BCG effectiveness in high-risk neonates in England may be lower than previously thought as we only observed a small decrease in incidence rates.

This study indicates that the change in England’s BCG vaccination policy was associated with a modest increase in incidence in the UK born that were relevant to the school-age vaccination programme, and with a small reduction in incidence in the UK born that were relevant to the high-risk neonatal vaccination programme. We found stronger evidence of an association between the change in policy and a decrease in incidence rates in the non-UK born populations relevant to both programmes. This suggests that the change of vaccination policy to target high-risk neonates may have resulted in an increased focus on high-risk non-UK born individuals who may not have been the direct targets of the vaccination programme. Further validation is required using alternative study designs, but this result should be considered when vaccination policy changes are being considered.

It is well established that interventions against infectious diseases, such as TB, should be evaluated not only for their direct effects but also for future indirect effects via ongoing transmission. Statistical approaches such as those used in this paper are not appropriate for capturing these future indirect effects, and instead dynamic disease models should be used. In addition, this study could not evaluate the impact of the neonatal programme on the high-risk population it targets, due to a lack of reliable data. Improved coverage data for the BCG programme is required to more fully evaluate its ongoing impact.

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**Contributors**

SA, HC, and EBP conceived and designed the work. SA undertook the analysis with advice from all other authors. All authors contributed to the interpretation of the data. SA wrote the first draft of the paper and all authors contributed to subsequent drafts. All authors approve the work for publication and agree to be accountable for the work.

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**Conflicts of interest**

HC reports receiving honoraria from Sanofi Pasteur, and consultancy fees from AstraZeneca, GSK and IMS Health, all paid to her employer.

**Accessibility of data and programming code** The code used to clean the data used in this paper can be found at: *link not yet available* The code for the analysis contained in this paper can be found at: *link not yet available*

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## Online supplementary appendix: Estimating the effect of the 2005 UK BCG vaccination policy change: A retrospective cohort study using the Enhanced Tuberculosis Surveillance system, 2000-2015

Sam Abbott, Hannah Christensen, Ellen Brooks-Pollock

**Model Definitions**

Supplementary Table S1: Full definition of each model, ordered by increasing complexity.

|  |  |
| --- | --- |
| Model | Description |
| Model 1 | Poisson model adjusting for no fixed effects. |
| Model 2 | Poisson model adjusting with fixed effects for the change in policy. |
| Model 3 | Poisson model adjusting with fixed effects for the change in policy and incidence rates in the UK born. |
| Model 4 | Poisson model adjusting with fixed effects for the change in policy and incidence rates in the non-UK born. |
| Model 5 | Poisson model adjusting with fixed effects for the change in policy and incidence rates in the UK born and non-UK born populations. |
| Model 6 | Poisson model adjusting with fixed effects for the change in policy and age. |
| Model 7 | Poisson model adjusting with fixed effects for the change in policy, age, and incidence rates in the UK born. |
| Model 7 (Negative Binomial) | Negative binomial model adjusting with fixed effects for the change in policy, age, and incidence rates in the UK born. |
| Model 8 | Poisson model adjusting with fixed effects for the change in policy, age, and incidence rates in the non-UK born. |
| Model 8 (Negative Binomial) | Negative binomial model adjusting with fixed effects for the change in policy, age, and incidence rates in the non-UK born. |
| Model 9 | Poisson model adjusting with fixed effects for the change in policy, age, and incidence rates in the UK born and non-UK born populations. |
| Model 10 | Poisson model with a random intercept for year of study entry, adjusting for no fixed effects. |
| Model 11 | Poisson model with a random intercept for year of study entry, adjusting with fixed effects for the change in policy. |
| Model 12 | Poisson model with a random intercept for year of study entry, adjusting with fixed effects for the change in policy and incidence rates in the UK born. |
| Model 13 | Poisson model with a random intercept for year of study entry, adjusting with fixed effects for the change in policy and incidence rates in the non-UK born. |
| Model 14 | Poisson model with a random intercept for year of study entry, adjusting with fixed effects for the change in policy and incidence rates in the UK born and non-UK born populations. |
| Model 15 | Poisson model with a random intercept for year of study entry, adjusting with fixed effects for the change in policy and age. |
| Model 16 | Poisson model with a random intercept for year of study entry, adjusting with fixed effects for the change in policy, age, and incidence rates in the UK born. |
| Model 16 (Negative Binomial) | Negative binomial model with a random intercept for year of study entry, adjusting with fixed effects for the change in policy, age, and incidence rates in the UK born. |
| Model 17 | Poisson model with a random intercept for year of study entry, adjusting with fixed effects for the change in policy, age, and incidence rates in the non-UK born. |
| Model 17 (Negative Binomial) | Negative binomial model with a random intercept for year of study entry, adjusting with fixed effects for the change in policy, age, and incidence rates in the non-UK born. |
| Model 18 | Poisson model with a random intercept for year of study entry, adjusting with fixed effects for the change in policy, age, and incidence rates in the UK born and non-UK born populations. |

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**Imputation of UK birth status**

As we were imputing a single variable we reformulated the imputation as a categorical prediction problem. This allowed us to use techniques from machine learning to improve the quality of our imputation, whilst also validating it using metrics supported by theory. We included year of notification, sex, age, Public Health England Centre (PHEC), occupation, ethnic group, Index of Multiple Deprivation (2010) categorised into five groups for England (IMD rank), and risk factor count (risk factors considered; drug use, homelessness, alcohol misuse/abuse and prison). However, we could not account for a possible missing not at random mechanism not captured by these covariates. To train the model we first split the data with complete UK birth status into a training set (80%), a calibration set (5%) and a test set (15%). We then fit a gradient boosted machine with the 10000 trees, early stopping (at a precision of , with 10 stopping rounds), a learning rate of 0.1, and a learn rate annealing of 0.99. Once the model had been fit to the training set we performed platt scaling using the calibration data set. Our fitted imputation model had a Logloss of 0.28 on the test set, with an AUC of 0.93, both of which indicate a robust out of bag performance. We found that ethnic group was the most important variable for predicting UK birth status, followed by age and PHEC.

Using the fitted model we predicted the birth status for notifications where this was missing, using the F1 optimal threshold as our probability cut-off. It is common to impute missing values multiple times, to account for within- and between imputation variability. However, we considered this unnecessary for our analysis as the amount of missing data was small, our analysis considered only aggregate counts, our model metrics indicated a robust level of performance out of bag and any unaccounted for uncertainty would be outweighed by the uncertainty in our population denominator.(11) We found that cases with imputed birth status had a similar proportion of UK born to non-UK born cases as in the complete data (Supplementary Table S6).

Supplementary Table S6: Comparision of UK birth status in cases with complete or imputed records.

|  |  |  |  |
| --- | --- | --- | --- |
| Status | Birth Status | Proportion of Cases (%) | Cases |
| Complete |  |  | 106765 |
|  | UK Born | 27.3 | 29096 |
|  | Non-UK Born | 72.7 | 77669 |
| Imputed |  |  | 8055 |
|  | UK Born | 32.7 | 2634 |
|  | Non-UK Born | 67.3 | 5421 |

Inclusion of imputed values for UK birth status should reduce bias caused by any missing not at random mechanism. Graphical evaluation of UK birth status indicated that missingness has reduced over time, indicating a missing not at random mechanism. If only the complete case data then incidence rates would have reduced over the study period due to this mechanism, this may have biased our estimate of the impact of then change in policy.

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**Estimating the magnitude of the estimated impact of the change in BCG policy**

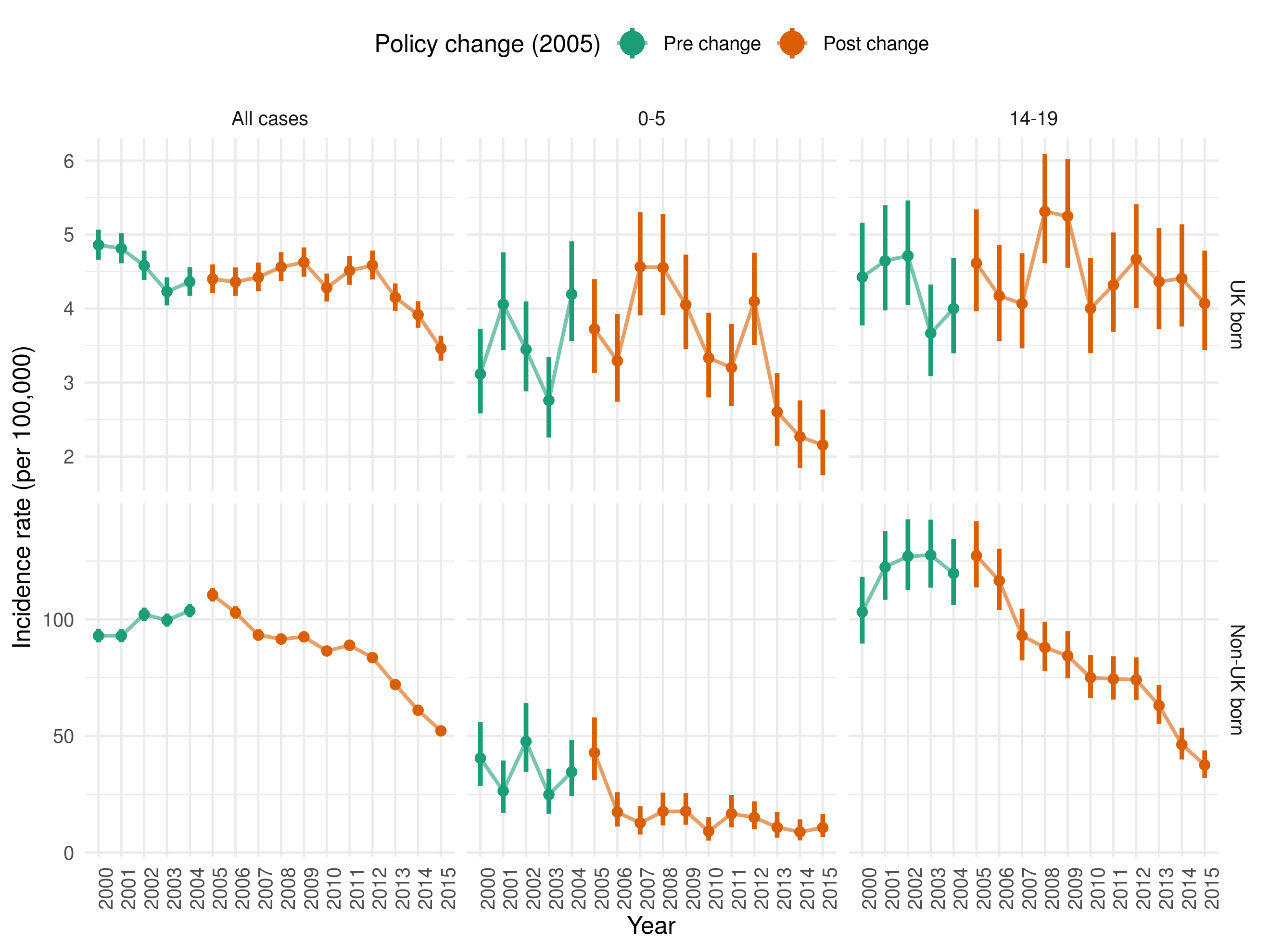
We estimated the magnitude of the estimated impact from the change in BCG policy by applying the IRR estimates from the best fitting model for each cohort to the observed number of notifications from 2005 until 2015 in our study population. For the cohorts relevant to the universal school-age vaccination scheme we estimated the number of prevented cases by first aggregating cases () and then using the following equation,

Where is the predicted number of cases prevented using the mean (), 2.5% bound () and 97.5% bound () of the IRR estimate . For the cohorts relevant to the targeted high-risk neonatal scheme we used a related equation, adjusting for the fact that the populations was exposed to the scheme and we therefore had to first estimate the number of cases that would have been observed had the scheme not been implemented. After simplification this results in the following equation,

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**Descriptive analysis of age-specific incidence rates**

From 2000 until 2012 incidence rates in the UK born remained relatively stable but have since fallen year on year. In comparison incidence rates in the non-UK born increased from 2000 until 2005, since when they have also decreased year on year. In 14-19 year old’s, who were UK born, incidence rates remained relatively stable throughout the study period, except for the period between 2006 to 2009 in which they increased year on year. This trend was not observed in the non-UK born population aged 14-19, where incidence rates reached a peak in 2003, since when they have consistently declined. In those aged 0-5, who were UK born, incidence rates also increased year on year after the change in BCG policy, until 2008 since when they have declined. This does not match with the observed trend in incidence rates in the non-UK born population, aged 0-5, in which incidence rates declined steeply between 2005 and 2006, since when they have remained relatively stable (Supplementary Figure S1; Supplementary Table S7; Supplementary Table S8).



Supplementary Figure S1: Incidence rates per 100,000 for UK born population and non-UK born population, aged 0-5 and therefore directly affected by the targeted neonatal vaccination programme, and aged 14-19 and therefore directly affected by the universal school-age scheme.

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**Incidence estimates for all cases, those aged 0-5 and those aged 14-19**

Supplementary Table S7: Incidence rates per 100,000 in the UK born for all cases, those aged 0-5, and those aged 14-19, who were directly affected by the change in vaccination policy in 2005

|  |  |  |  |
| --- | --- | --- | --- |
| Year eligible for vaccination | Age group | | |
| All cases\* | 0-5\* | 14-19\* |
| 2000 | 4.86 (4.66, 5.07) | 3.12 (2.58, 3.73) | 4.43 (3.77, 5.16) |
| 2001 | 4.81 (4.61, 5.02) | 4.06 (3.44, 4.76) | 4.65 (3.98, 5.40) |
| 2002 | 4.58 (4.39, 4.78) | 3.45 (2.88, 4.10) | 4.71 (4.05, 5.46) |
| 2003 | 4.23 (4.04, 4.42) | 2.76 (2.26, 3.34) | 3.67 (3.09, 4.33) |
| 2004 | 4.36 (4.17, 4.56) | 4.19 (3.56, 4.91) | 4.00 (3.40, 4.68) |
| 2005 | 4.40 (4.21, 4.60) | 3.72 (3.13, 4.40) | 4.61 (3.96, 5.34) |
| 2006 | 4.36 (4.17, 4.56) | 3.29 (2.74, 3.93) | 4.17 (3.56, 4.86) |
| 2007 | 4.42 (4.23, 4.62) | 4.57 (3.91, 5.30) | 4.07 (3.46, 4.75) |
| 2008 | 4.56 (4.37, 4.76) | 4.56 (3.91, 5.28) | 5.31 (4.61, 6.09) |
| 2009 | 4.63 (4.43, 4.83) | 4.05 (3.45, 4.73) | 5.25 (4.55, 6.02) |
| 2010 | 4.28 (4.09, 4.47) | 3.33 (2.80, 3.94) | 4.00 (3.40, 4.68) |
| 2011 | 4.51 (4.32, 4.71) | 3.20 (2.69, 3.79) | 4.32 (3.69, 5.03) |
| 2012 | 4.59 (4.39, 4.78) | 4.10 (3.51, 4.76) | 4.67 (4.00, 5.41) |
| 2013 | 4.15 (3.97, 4.34) | 2.60 (2.15, 3.13) | 4.36 (3.72, 5.09) |
| 2014 | 3.92 (3.74, 4.10) | 2.27 (1.85, 2.76) | 4.41 (3.76, 5.14) |
| 2015 | 3.46 (3.30, 3.63) | 2.16 (1.75, 2.64) | 4.07 (3.44, 4.78) |
| \* Incidence rate per 100,000, with 95% confidence intervals | | | |

Supplementary Table S8: Incidence rates per 100,000 in the non-UK born for all cases, those aged 0-5, and those aged 14-19, who would have been directly affected by the change in vaccination policy in 2005 had they been UK born

|  |  |  |  |
| --- | --- | --- | --- |
| Year eligible for vaccination | Age group | | |
| All cases\* | 0-5\* | 14-19\* |
| 2000 | 92.98 (90.10, 95.92) | 40.45 (28.56, 55.88) | 103.14 (89.60, 118.19) |
| 2001 | 92.95 (90.12, 95.84) | 26.36 (16.95, 39.47) | 122.40 (108.32, 137.85) |
| 2002 | 102.07 (99.18, 105.03) | 47.63 (34.62, 64.16) | 127.03 (112.59, 142.83) |
| 2003 | 99.65 (96.85, 102.50) | 24.81 (16.59, 35.94) | 127.53 (113.57, 142.75) |
| 2004 | 103.66 (100.82, 106.56) | 34.58 (24.13, 48.25) | 119.66 (106.18, 134.41) |
| 2005 | 110.48 (107.64, 113.37) | 42.83 (30.99, 57.91) | 127.26 (113.69, 142.04) |
| 2006 | 102.91 (100.28, 105.59) | 17.32 (11.13, 25.93) | 116.54 (103.91, 130.31) |
| 2007 | 93.26 (90.85, 95.71) | 12.69 (7.74, 19.87) | 92.99 (82.40, 104.58) |
| 2008 | 91.52 (89.19, 93.90) | 17.59 (11.66, 25.67) | 87.92 (77.84, 98.97) |
| 2009 | 92.47 (90.17, 94.82) | 17.69 (11.92, 25.44) | 84.34 (74.71, 94.90) |
| 2010 | 86.41 (84.21, 88.67) | 9.07 (5.11, 15.16) | 75.00 (66.19, 84.68) |
| 2011 | 88.88 (86.70, 91.10) | 16.65 (10.82, 24.70) | 74.41 (65.59, 84.12) |
| 2012 | 83.60 (81.51, 85.73) | 15.05 (9.97, 21.96) | 74.12 (65.45, 83.65) |
| 2013 | 72.03 (70.13, 73.97) | 10.80 (6.36, 17.41) | 63.04 (55.16, 71.77) |
| 2014 | 61.01 (59.29, 62.78) | 8.82 (5.19, 14.22) | 46.31 (39.90, 53.49) |
| 2015 | 52.18 (50.62, 53.77) | 10.69 (6.62, 16.54) | 37.55 (31.97, 43.83) |
| \* Incidence rate per 100,000, with 95% confidence intervals | | | |

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**Direct effects of the change in policy on the UK born cohorts - results from all models**

Supplementary Table S2: Comparison of models fitted to incidence rates for the UK born population that were relevant to the universal vaccination programme of those at school-age (14). Models are ordered by the goodness of fit as assessed by LOOIC, the degrees of freedom are used as a tiebreaker.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Model | IRR (CI 95%)\* | Variable | | | | | DoF\*\* | LPD† | LOOIC (se)†† |
| Policy Change | Age | UK born rates | Non-UK born rates | Year of study entry |
| Model 7 (Negative Binomial) | 1.08 (0.97, 1.19) | Yes | Yes | Yes | No | No | 9 | -211 | 439 (10) |
| Model 7 | 1.08 (1.00, 1.17) | Yes | Yes | Yes | No | No | 8 | -211 | 443 (14) |
| Model 9 | 1.12 (1.01, 1.25) | Yes | Yes | Yes | Yes | No | 9 | -210 | 445 (14) |
| Model 16 | 1.08 (0.97, 1.21) | Yes | Yes | Yes | No | Yes | 20 | -207 | 445 (14) |
| Model 18 | 1.12 (0.97, 1.28) | Yes | Yes | Yes | Yes | Yes | 21 | -207 | 447 (15) |
| Model 8 | 1.16 (1.04, 1.29) | Yes | Yes | No | Yes | No | 8 | -213 | 449 (17) |
| Model 6 | 1.06 (0.98, 1.15) | Yes | Yes | No | No | No | 7 | -215 | 452 (17) |
| Model 17 | 1.15 (1.00, 1.32) | Yes | Yes | No | Yes | Yes | 20 | -209 | 452 (17) |
| Model 15 | 1.06 (0.94, 1.20) | Yes | Yes | No | No | Yes | 19 | -209 | 453 (17) |
| Model 1 | 0.00 (0.00, 0.00) | No | No | No | No | No | 1 | -254 | 513 (26) |
| Model 2 | 1.06 (0.98, 1.14) | Yes | No | No | No | No | 2 | -252 | 515 (25) |
| Model 4 | 1.00 (0.90, 1.10) | Yes | No | No | Yes | No | 3 | -251 | 516 (25) |
| Model 3 | 1.06 (0.98, 1.15) | Yes | No | Yes | No | No | 3 | -252 | 518 (26) |
| Model 5 | 0.98 (0.89, 1.09) | Yes | No | Yes | Yes | No | 4 | -249 | 518 (24) |
| Model 13 | 0.94 (0.78, 1.12) | Yes | No | No | Yes | Yes | 15 | -237 | 518 (27) |
| Model 10 | 0.00 (0.00, 0.00) | No | No | No | No | Yes | 13 | -244 | 521 (28) |
| Model 11 | 1.06 (0.94, 1.20) | Yes | No | No | No | Yes | 14 | -244 | 522 (28) |
| Model 14 | 0.93 (0.78, 1.11) | Yes | No | Yes | Yes | Yes | 16 | -236 | 522 (27) |
| Model 12 | 1.06 (0.93, 1.20) | Yes | No | Yes | No | Yes | 15 | -243 | 526 (28) |
| \* Incidence Rate Ratio, with 95% credible intervals,  \*\* Degrees of Freedom,  † Computed log pointwise predictive density,  †† Leave one out information criterion, with standard error | | | | | | | | | |

Supplementary Table S4: Comparison of models fitted to incidence rates for the UK born population that were elgible to the targeted vaccination programme of neonates. Models are ordered by the goodness of fit as assessed by LOOIC, the degrees of freedom are used as a tiebreaker.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Model | IRR (CI 95%)\* | Variable | | | | | DoF\*\* | LPD† | LOOIC (se)†† |
| Policy Change | Age | UK born rates | Non-UK born rates | Year of study entry |
| Model 16 | 0.96 (0.82, 1.14) | Yes | Yes | Yes | No | Yes | 20 | -192 | 415 (12) |
| Model 16 (Negative Binomial) | 0.96 (0.82, 1.13) | Yes | Yes | Yes | No | Yes | 21 | -196 | 415 (10) |
| Model 16 (Negative Binomial) | 0.96 (0.82, 1.13) | Yes | Yes | Yes | No | Yes | 21 | -196 | 415 (10) |
| Model 18 | 0.99 (0.82, 1.18) | Yes | Yes | Yes | Yes | Yes | 21 | -192 | 417 (13) |
| Model 7 | 0.96 (0.88, 1.05) | Yes | Yes | Yes | No | No | 8 | -200 | 420 (15) |
| Model 9 | 1.00 (0.89, 1.12) | Yes | Yes | Yes | Yes | No | 9 | -200 | 422 (15) |
| Model 8 | 1.02 (0.91, 1.15) | Yes | Yes | No | Yes | No | 8 | -203 | 427 (16) |
| Model 6 | 0.95 (0.87, 1.03) | Yes | Yes | No | No | No | 7 | -204 | 428 (16) |
| Model 15 | 0.95 (0.83, 1.09) | Yes | Yes | No | No | Yes | 19 | -198 | 428 (14) |
| Model 17 | 1.02 (0.87, 1.20) | Yes | Yes | No | Yes | Yes | 20 | -198 | 429 (14) |
| Model 14 | 1.10 (0.92, 1.33) | Yes | No | Yes | Yes | Yes | 16 | -206 | 442 (16) |
| Model 5 | 1.08 (0.97, 1.21) | Yes | No | Yes | Yes | No | 4 | -216 | 445 (18) |
| Model 12 | 0.98 (0.83, 1.15) | Yes | No | Yes | No | Yes | 15 | -209 | 448 (17) |
| Model 4 | 1.12 (1.00, 1.24) | Yes | No | No | Yes | No | 3 | -219 | 449 (18) |
| Model 3 | 0.97 (0.89, 1.06) | Yes | No | Yes | No | No | 3 | -219 | 450 (19) |
| Model 13 | 1.14 (0.97, 1.35) | Yes | No | No | Yes | Yes | 15 | -211 | 452 (16) |
| Model 1 | 0.00 (0.00, 0.00) | No | No | No | No | No | 1 | -229 | 462 (21) |
| Model 2 | 0.95 (0.87, 1.03) | Yes | No | No | No | No | 2 | -228 | 463 (20) |
| Model 10 | 0.00 (0.00, 0.00) | No | No | No | No | Yes | 13 | -220 | 466 (19) |
| Model 11 | 0.95 (0.83, 1.09) | Yes | No | No | No | Yes | 14 | -219 | 467 (19) |
| \* Incidence Rate Ratio, with 95% credible intervals,  \*\* Degrees of Freedom,  † Computed log pointwise predictive density,  †† Leave one out information criterion, with standard error | | | | | | | | | |

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**Direct effects of the change in policy on the non-UK born cohorts - results from all models**

Supplementary Table S3: Comparison of models fitted to incidence rates for the non-UK born population that were eligible to the universal vaccination programme of those at school-age (14). Models are ordered by the goodness of fit as assessed by LOOIC, the degrees of freedom are used as a tiebreaker.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Model | IRR (CI 95%)\* | Variable | | | | | DoF\*\* | LPD† | LOOIC (se)†† |
| Policy Change | Age | UK born rates | Non-UK born rates | Year of study entry |
| Model 17 (Negative Binomial) | 0.74 (0.61, 0.88) | Yes | Yes | No | Yes | Yes | 21 | -228 | 483 (10) |
| Model 17 | 0.74 (0.62, 0.87) | Yes | Yes | No | Yes | Yes | 20 | -223 | 492 (16) |
| Model 18 | 0.73 (0.61, 0.87) | Yes | Yes | Yes | Yes | Yes | 21 | -222 | 493 (16) |
| Model 15 | 0.64 (0.53, 0.78) | Yes | Yes | No | No | Yes | 19 | -224 | 496 (18) |
| Model 16 | 0.65 (0.54, 0.78) | Yes | Yes | Yes | No | Yes | 20 | -223 | 496 (17) |
| Model 8 | 0.79 (0.73, 0.86) | Yes | Yes | No | Yes | No | 8 | -239 | 507 (20) |
| Model 9 | 0.79 (0.72, 0.86) | Yes | Yes | Yes | Yes | No | 9 | -238 | 511 (20) |
| Model 11 | 0.64 (0.52, 0.78) | Yes | No | No | No | Yes | 14 | -241 | 522 (22) |
| Model 10 | 0.00 (0.00, 0.00) | No | No | No | No | Yes | 13 | -241 | 523 (22) |
| Model 12 | 0.64 (0.53, 0.79) | Yes | No | Yes | No | Yes | 15 | -241 | 525 (22) |
| Model 13 | 0.64 (0.52, 0.79) | Yes | No | No | Yes | Yes | 15 | -241 | 526 (23) |
| Model 14 | 0.64 (0.52, 0.79) | Yes | No | Yes | Yes | Yes | 16 | -241 | 530 (23) |
| Model 7 | 0.66 (0.62, 0.70) | Yes | Yes | Yes | No | No | 8 | -248 | 532 (23) |
| Model 6 | 0.65 (0.61, 0.69) | Yes | Yes | No | No | No | 7 | -253 | 539 (27) |
| Model 4 | 0.70 (0.65, 0.76) | Yes | No | No | Yes | No | 3 | -270 | 556 (31) |
| Model 5 | 0.70 (0.64, 0.76) | Yes | No | Yes | Yes | No | 4 | -270 | 559 (31) |
| Model 2 | 0.65 (0.61, 0.69) | Yes | No | No | No | No | 2 | -275 | 561 (33) |
| Model 3 | 0.65 (0.61, 0.69) | Yes | No | Yes | No | No | 3 | -273 | 561 (32) |
| Model 1 | 0.00 (0.00, 0.00) | No | No | No | No | No | 1 | -341 | 692 (51) |
| \* Incidence Rate Ratio, with 95% credible intervals,  \*\* Degrees of Freedom,  † Computed log pointwise predictive density,  †† Leave one out information criterion, with standard error | | | | | | | | | |

Supplementary Table S5: Comparison of models fitted to incidence rates for the non-UK born population that were revelant to the targeted vaccination programme of neonates. Models are ordered by the goodness of fit as assessed by LOOIC, the degrees of freedom are used as a tiebreaker.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Model | IRR (CI 95%)\* | Variable | | | | | DoF\*\* | LPD† | LOOIC (se)†† |
| Policy Change | Age | UK born rates | Non-UK born rates | Year of study entry |
| Model 8 (Negative Binomial) | 0.62 (0.44, 0.88) | Yes | Yes | No | Yes | No | 9 | -138 | 293 (15) |
| Model 8 | 0.64 (0.47, 0.86) | Yes | Yes | No | Yes | No | 8 | -137 | 295 (18) |
| Model 9 | 0.62 (0.45, 0.85) | Yes | Yes | Yes | Yes | No | 9 | -137 | 297 (18) |
| Model 6 | 0.47 (0.38, 0.58) | Yes | Yes | No | No | No | 7 | -139 | 298 (19) |
| Model 7 | 0.48 (0.39, 0.60) | Yes | Yes | Yes | No | No | 8 | -139 | 298 (19) |
| Model 17 | 0.63 (0.44, 0.89) | Yes | Yes | No | Yes | Yes | 20 | -135 | 298 (18) |
| Model 18 | 0.61 (0.42, 0.87) | Yes | Yes | Yes | Yes | Yes | 21 | -135 | 300 (18) |
| Model 15 | 0.47 (0.35, 0.62) | Yes | Yes | No | No | Yes | 19 | -136 | 301 (20) |
| Model 16 | 0.48 (0.36, 0.63) | Yes | Yes | Yes | No | Yes | 20 | -136 | 301 (19) |
| Model 4 | 0.82 (0.61, 1.10) | Yes | No | No | Yes | No | 3 | -147 | 304 (17) |
| Model 5 | 0.78 (0.58, 1.06) | Yes | No | Yes | Yes | No | 4 | -147 | 306 (18) |
| Model 13 | 0.83 (0.59, 1.16) | Yes | No | No | Yes | Yes | 15 | -145 | 308 (18) |
| Model 14 | 0.78 (0.55, 1.12) | Yes | No | Yes | Yes | Yes | 16 | -144 | 310 (19) |
| Model 3 | 0.52 (0.42, 0.64) | Yes | No | Yes | No | No | 3 | -152 | 314 (22) |
| Model 12 | 0.51 (0.38, 0.69) | Yes | No | Yes | No | Yes | 15 | -148 | 317 (23) |
| Model 2 | 0.49 (0.40, 0.61) | Yes | No | No | No | No | 2 | -156 | 319 (22) |
| Model 11 | 0.49 (0.37, 0.65) | Yes | No | No | No | Yes | 14 | -152 | 322 (23) |
| Model 10 | 0.00 (0.00, 0.00) | No | No | No | No | Yes | 13 | -150 | 330 (25) |
| Model 1 | 0.00 (0.00, 0.00) | No | No | No | No | No | 1 | -171 | 346 (27) |
| \* Incidence Rate Ratio, with 95% credible intervals,  \*\* Degrees of Freedom,  † Computed log pointwise predictive density,  †† Leave one out information criterion, with standard error | | | | | | | | | |