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Modelling the impact of prison vaccination on hepatitis B transmission within the injecting drug user population of England and Wales

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Abstract

A vaccination programme offering hepatitis B (HBV) vaccine at reception into prison has been introduced into selected prisons in England and Wales. The work here considers the impact of prison vaccination on the incidence and prevalence of hepatitis B virus (HBV) in the injecting drug user (IDU) population of England and Wales. A dynamic model of the transmission of HBV in IDUs is developed with key model assumptions and parameters being subject to sensitivity analyses.

The base case model (that assumes that the vaccination coverage on prison reception is 5% in 2002, 10% in 2003 and then increases linearly up to 50% of prison receptions being vaccinated by 2006) predicts that the incidence of HBV in IDUs might be reduced by almost 80% in 12 years, and the HBV prevalence (IDUs ever infected by HBV) may be reduced from approximately 18% in 2002 to 7% in 2015.

The model presented here demonstrates that HBV vaccination on prison reception can have a significant impact on the prevalence and incidence of HBV in the IDU population over time.

Keywords: Hepatitis B vaccination; Injecting drug users; Prison

1. Introduction

Individuals that make up the injecting drug user (IDU) population in England and Wales are at risk from blood-borne viruses [1], due to the sharing of injecting paraphernalia. Data collected by the Health Protection Agency (HPA) in 2003 [2] suggested that amongst those cases of acute hepatitis B with an identified risk factor, 34% are attributable to injecting drug use. Many IDUs will spend some time incarcerated in prison [3] and so prison provides an opportunity to vaccinate this hard to reach group against HBV. Data from the Unlinked Anonymous Prevalence Monitoring Programme survey of IDUs in contact with drug agencies in England and Wales has shown that HBV vaccine uptake (receiving one or more vaccine doses) in the IDU population has shown a steady increase since 1998 up to over 40% in 2003 [2]. However, the overall HBV vaccination coverage in the IDU population is likely to be lower than this as many IDUs are not in contact with drug agencies.

A model describing the IDU population and its flow through prison has been developed that shows the potential coverage of the HBV vaccination programme in prisons and the number of IDUs that may be vaccinated over time [4]. This work demonstrated that over a range of vaccination scenarios, 57% of the IDU population might be vaccinated by 2012 if coverage of 50% or more on prison reception could be achieved across all prisons in England and Wales. However, this model does not show the impact that this vaccination programme may have on the transmission of HBV within the IDU population in England and Wales.

The model proposed here describes the dynamics of HBV transmission in the IDU population of England and Wales. The work here takes estimates of the proportion of the IDU

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population vaccinated from the model of the HBV vaccination programme in prisons under a range of vaccination scenarios and considers the effect of this programme on the incidence of HBV in the IDU population in England and Wales. Sensitivity analysis of the key model assumptions and parameters is undertaken.

2. Methods

The model presented here considers the transmission of HBV due to contact between IDUs. This represents the sharing of injecting paraphernalia and other at-risk practices that may lead to the transmission of blood-borne viruses; this may also include the potential for transmission via sexual contact between IDUs.

2.1. Model structure

Only the IDU population of England and Wales is considered with non-IDUs being excluded from this analysis, and it is assumed that the IDU population is of fixed size and equal to 160,000 [5]. The results from the model of the HBV vaccination programme in prisons in England and Wales have been used here [4], and as this model considers only males, it has been assumed here that female IDUs have the same offending characteristics as males. A brief review of this model is described later.

Using a mathematical model of HBV natural history and transmission dynamics [6–8], the IDU population is stratified into six epidemiological groups: those who are susceptible to infection, denoted (S); those who have been infected but are not yet infectious, (L); acute infections, (A), who are in the initial highly infectious stage of infection; those who are carriers, (C); vaccinated, (V), those that have been vaccinated and are immune from infection; and those with protective immunity, (R), due to recovery from either carrier or acute stages of infection. As the model includes an injecting career length dependent force of infection (FOI) defined as the per capita rate at which susceptibles become infected, the IDU population is stratified by injecting career length.

IDUs enter the model at the start of the year into the first injecting career length cohort. Thereafter individuals change cohorts at the beginning of each new year. The rates, with respect to both injecting career length and time, at which individuals flow from one epidemiological state to another, are described by a system of differential equations (Appendix A).

2.1.1. Modelling the HBV vaccination programme in prisons

A model has been developed to assess the potential impact of the HBV vaccination programme in prisons in England and Wales on the vaccination coverage of prisoners, ex-prisoners, and injecting drug users. The model describes non-IDUs and IDUs as they flow through prison, start and stop injecting drugs, and return to prison due to recidivist behaviour. Over a range of vaccination coverage scenarios, the model predicts the change over time in the vaccination status of new entrants to prison, current prisoners and injecting drugs users (IDUs) in the community. The model predicts up to 72% of the injecting drug user population may be vaccinated depending on the vaccination scenario implemented. These results were found to be sensitive to the size of the IDU population in England and Wales and the average time served by an IDU during each prison visit. This paper is available on request [4].

2.2. Parameterisation

2.2.1. IDU population data

It has been assumed that an IDU has an average injecting career length of 5.97 years. This estimate is taken from a previous study in which an age-structured model describing the initiation of injecting and the removal of injectors from the IDU population and their evolution over time was fitted to data by maximum likelihood [9]. Coupled with the fixed IDU population size of 160,000 this leads to $\alpha = 26{,}801$ IDUs starting injecting each year. The removal rates are defined as the rates that IDUs leave the IDU population due to either the cessation of injecting or death. Assuming that the age dependent removal rates from a previous study [9] are a reasonable approximation of the rate at which IDUs leave the IDU population, to be compatible with the model presented here, these removal rates are converted to be injecting career length dependent (see Appendix A).

2.3. The force of infection and transmission coefficients

The FOI estimates presented here are taken from a previous study [10] (available on request) in which data from voluntary unlinked anonymous surveys performed on IDUs in contact with specialist agencies throughout England and Wales were used to derive maximum likelihood estimates of the FOI for HBV, hepatitis C, and HIV in the IDU population and how these may vary with injecting career length and have evolved over time. This study considered the IDU population as being divided into two groups which have been adopted here; new initiates, i.e. those injectors with an injecting career length of less than 1 year, and experienced IDUs, i.e. those injectors with an injecting career length of greater than 1 year. It was found that the FOI for HBV had not changed from 1999 to 2002 and so it is assumed here that the FOI is constant within both of the discrete injecting career length groups (see Appendix A) prior to the introduction of prison vaccination.

The transmission coefficients, β_{mn}, are the per capita rate of effective contact between two IDUs of career length m and n (where an index = 1 represents those with an injecting career length of less than 1 year; and 2 represents those with a career length of more than 1 year). They were calculated

Table 1
The structure of the WAIFM matrix (β_{ij}) with values at baseline

i	j	
	1	2
1	7.50×10^{-5}	4.62×10^{-5}
2	4.62×10^{-5}	2.85×10^{-5}

The injecting career length groups (numbered 1 to 2) refer to <1 year, and 1+ years, respectively.

from the equilibrium values of λ_n the FOI for individuals in group n and the number of carriers and acutes in the population at steady state assuming proportional mixing. This type of mixing arises when individuals make contacts with other people in their own or other groups in proportion to the number of contacts that are supplied from each group [11] (see Appendix A).

The estimates of the transmission coefficients for the 'Who acquires infection from whom' (WAIFM) matrix are shown in Table 1.

A summary of parameters is given in Table 2 along with a reference to the data source as appropriate.

2.4. Sensitivity analysis

To test the effect of the model assumptions on the results obtained from the model a number of different tests of sensitivity were undertaken, these are listed below:

1. Alternative values for the FOI in new initiates and experienced IDUs were applied. These estimates taken from a previous study [10] are the values of the upper and lower 95% confidence intervals of the baseline values, and an estimate of the FOI that is equal for both new initiates and experienced IDUs (Upper, Lower, and Equal). These are shown in Table 3.

Table 2
Baseline parameter estimates used in numerical simulations

Parameter	Symbol	Value	Data sources
Force of infection in new initiates prior to the introduction of prison vaccination	λ_1	0.0936 per year	[10]
Force of infection in experienced IDUs prior to the introduction of prison vaccination	λ_2	0.0577 per year	[10]
IDU population size		160000	[5]
Rate of lose of latency	σ	6 per year	[7]
Recovery rate (acutes)	γ_1	4 per year	[7]
Recovery rate (carriers)	γ_2	0.25 per year	[7]
The proportion of those with acute infection that become a carrier	p	0.05	[7]
Relative infectiousness of carriers	δ	0.16	[7]

Table 3
FOI estimates (per person per year) used during sensitivity analysis

FOI	λ_1	λ_2
Upper	0.1270	0.1170
Lower	0.0635	0.0264
Equal	0.0684	0.0684

Table 4
Values of the transmission coefficients (per year) as used during sensitivity analysis for: (a) Mixing 1 and (b) Mixing 2

	$i=1$	$i=2$
(a) Mixing 1		
$i=1$	1.48×10^{-4}	4.11×10^{-5}
$i=2$	4.11×10^{-5}	4.11×10^{-5}
(b) Mixing 2		
$i=1$	2.80×10^{-4}	
$i=2$		5.40×10^{-5}

2. To test the assumption of proportional mixing, the effects of alternative values of the transmission coefficients on model results were investigated. The first set of values assume that new initiates and experienced IDUs mix at the same rate as experienced IDUs mix amongst themselves (Mixing 1), and the second set of values assumes that there is no mixing between new initiates and experienced IDUs (Mixing 2). The mixing matrices for each of these mixing assumptions (using the baseline FOI) is summarised in Table 4.

2.5. Vaccination scenarios

A summary of the vaccination scenarios implemented is provided in Table 5. The vaccination rates for the vaccination scenarios are calculated from the results obtained from the model of the prison vaccination programme [4]. They are for those IDUs that receive two or more doses of HBV vaccine and incorporate the possibility that an IDU may be vaccinated either in the community or in the prison. It is assumed that an IDU is protected from HBV if they have received 2+ doses of vaccine. The rates for a selection of the scenarios stratified by year and injecting career length are shown in Tables 6 and 7. Experienced IDUs are more likely to have been incarcerated in the past than new initiates, and as recidivists are more likely to go to prison than first time offenders, this explains the higher vaccination rates for experienced IDUs compared to new initiates which can be seen for all scenarios (Tables 6 and 7). As the focus of this study is the impact of prison vaccination, the vaccination rate for IDUs in the community is taken at a constant value for all vaccination scenarios estimated to be 0.106/IDU/year [4]. For all vaccination scenarios where vaccination is administered on prison reception, at each vaccination event 38% receive one dose of vaccine, 28% receive two doses of vaccine, and 34% receive three doses of vaccine. These statistics were taken from the reporting of the HBV vaccination programme in prisons from January to June 2003.

Table 5
Summary of vaccination scenarios

Vaccination scenario	Description
England and Wales (Scenarios A, B, and C)	Vaccination coverage is administered to prisoners on reception into prison; coverage is 5% in 2002, 10% in 2003 and then a linear increase up to 33% for scenario A, 50% for scenario B, and 66% for scenario C in 2006. Coverage is constant thereafter (Table 6)
Age specific	Vaccination coverage is administered from 2002 on reception into prison targeting specific age groups. The age groups independently targeted are 15–17 years, 18–29 years or 30+ years with coverage that is constant over time of 30, 70 or 100%
Equilibrium	Vaccination coverage is administered on reception into prison from 2002 onwards at a constant rate until equilibrium has been reached. A number of alternative levels of vaccination coverage are examined to see which would result in the HBV prevalence (IDUs ever infected) reaching zero (Table 7)
Campaign	Ninety percent of prisoners receive three doses of vaccine in 2003, and then from this point on vaccination on reception into prison is introduced at 80% coverage This represents a possible scenario where a strong commitment to vaccinate all prison inmates is introduced as was the case recently in Scotland [19]. An alternative to this scenario sees 90% of prisoners receive three doses of vaccine in 2003, 2006, and 2009 with no further vaccination administered in prison

Table 6
Vaccination rates/IDU/year for scenarios A, B, and C for England and Wales applied to new initiates and experienced IDUs

Year	Scenario					
	New initiates			Experienced IDUs		
	A	B	C	A	B	C
2002	0.01	0.01	0.01	0.13	0.13	0.13
2003	0.02	0.02	0.02	0.13	0.13	0.13
2004	0.04	0.04	0.04	0.13	0.13	0.13
2005	0.06	0.07	0.09	0.14	0.14	0.14
2006	0.08	0.11	0.14	0.15	0.15	0.15
2007	0.11	0.15	0.20	0.16	0.17	0.18
2008	0.11	0.16	0.21	0.17	0.19	0.22
2009	0.11	0.16	0.21	0.19	0.21	0.24
2010	0.12	0.17	0.22	0.19	0.23	0.26
2011	0.12	0.17	0.22	0.20	0.24	0.28
2012	0.12	0.17	0.22	0.21	0.24	0.28
2013	0.12	0.18	0.23	0.21	0.25	0.29
2014	0.13	0.18	0.23	0.21	0.25	0.29
2015	0.13	0.18	0.23	0.21	0.25	0.29

Where each scenario assumes a vaccination coverage of 5% on prison reception in 2002, 10% in 2003 and then a linear increase of up to constant 33% in 2006 for Scenario A, 50% for Scenario B, and 66% for Scenario C [7].

3. Results

The results for each of the vaccination scenarios described in the methods are shown below. In all cases HBV prevalence is defined as the proportion of IDUs in the overall population that have ever been infected by HBV, i.e. having antibody to HBV (anti-HBc), while the acute infections here may be symptomatic or asymptomatic.

Table 7
Vaccination rates/IDU/year for the equilibrium scenarios applied to new initiates and experienced IDUs

Vaccination coverage on reception into prison implemented from 2002 onwards (%)	New initiates	Experienced IDUs
5	0.03	0.14
10	0.05	0.15
15	0.07	0.17
20	0.09	0.18
25	0.11	0.19

3.1. England and Wales scenarios

Prior to the introduction of the prison vaccination programme it is estimated that despite the presence of community vaccination there were approximately 326 new initiates and over 912 experienced IDUs acutely infected from HBV in England and Wales in 2002. The overall HBV prevalence in the IDU population in 2002 was 18% with the HBV prevalence in new initiates and experienced IDUs being 7 and 20%, respectively.

If there had been no community vaccination prior to 2002, then it is estimated that the prevalence of HBV in 2002 in the IDU population would be over 22% (approximately 8% and 26% in new initiates and experienced IDUs, respectively). No community vaccination would lead to the annual number of acute infections in new initiates and experienced IDUs being estimated at 328 and 1279, respectively.

The impact of prison vaccination on the incidence of HBV in new initiates and experienced IDUs within the overall IDU population of England and Wales is shown in Fig. 1. The results show that as the vaccination rate increases over time the incidence of HBV in both new initiates and experienced IDUs decreases over time. A high proportion of the total number of acute infections of HBV in new initiates can be seen with over 25% occurring in the new initiates across all years.

The implementation of the baseline vaccination scenario (scenario B) results in the total number of acute cases of HBV being reduced by approximately 35% by 2008 and then by almost 80% in 2014. If vaccination coverage can reach 66% of all prison receptions by 2006 (scenario C) then the total acute cases within the IDU population can be reduced by approximately 40% in 2008 and 85% by 2014. However even if the vaccination coverage on prison reception only reaches 33% of all prison receptions by 2006 (scenario A) then the total acute cases within the IDU population will still be reduced by approximately 27% in 2008 and 65% by 2014.

The impact of the England and Wales scenarios on HBV prevalence in England and Wales in 2015 is shown in Fig. 2. It can be seen that assuming that the characteristics of the

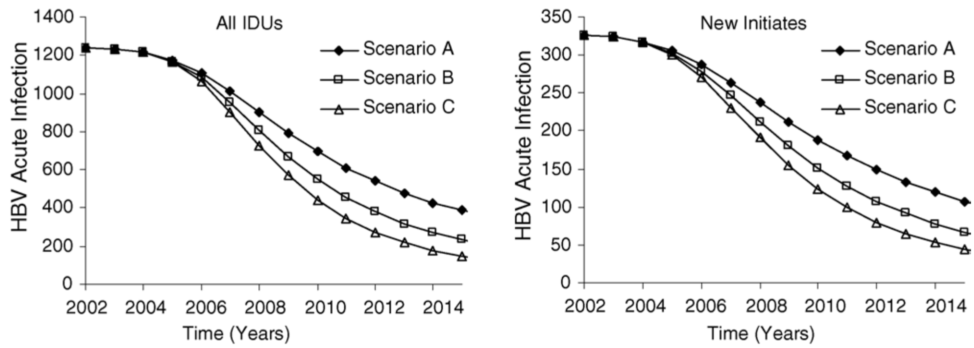

Fig. 1. The estimated annual number of acute infections of HBV in the IDU population and new initiates with variations in the prison vaccination scenario.

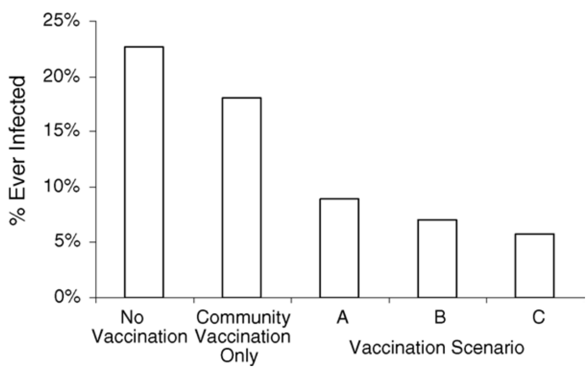

Fig. 2. The estimated HBV prevalence in IDUs in 2015 with variations in the vaccination scenario implemented.

IDU population do not significantly change over this period and there is no vaccination either in prison or the community, the HBV prevalence in 2015 will be approximately 22%. If vaccination is implemented on reception into prison and coupled with community vaccination (scenarios A, B, and C), it is estimated that HBV prevalence in the IDU population can be reduced to fewer than 10% by 2015.

3.2. Age specific scenarios

The impact of applying alternative age specific vaccination scenarios on the HBV prevalence in the IDU population in 2015 is shown in Table 8. It can be seen that a targeted vaccination strategy targeting 18–29 years which represents 49% of the prison population at 30% coverage has a substantial effect on HBV prevalence reducing it by almost 50%. In the case of the 15–17 year olds, it is unsurprising to find that targeting this age group was the least effective vaccination strategy given that this age group represents only 4% of the prison population. However, despite approximately 47% of the prison population being represented by over 30 year olds, targeting this age group for prison vaccination was still found to be largely ineffective [12].

Table 8
The impact of alternative age specific vaccination scenarios on the HBV prevalence in the IDU population in 2015

Coverage (%)	Age group vaccinated			
	15–17	18–29	30+	All
0	18.1%	18.1%	18.1%	18.1%
30	16.7%	9.7%	16.0%	7.8%
70	15.3%	4.8%	14.5%	3.6%
100	14.4%	3.4%	13.3%	2.5%

3.3. Equilibrium scenario results

It can be seen (Fig. 3) that the HBV prevalence within the IDU population may reach zero when the vaccination coverage on prison reception is between 20% and 25%. While this result is subject to a number of caveats and may not occur for many years (000s) it does show the potential long term impact of the HBV vaccination programme on prison reception on HBV transmission within the IDU population.

3.4. Campaign scenarios

The impact of two alternative campaign vaccination scenarios described in the methods is shown in Fig. 4. It can be seen that if a campaign is administered in 2003 and this is followed up by a high level of vaccination coverage on prison reception, this can have a significant effect on the HBV prevalence within the IDU population dropping to less than

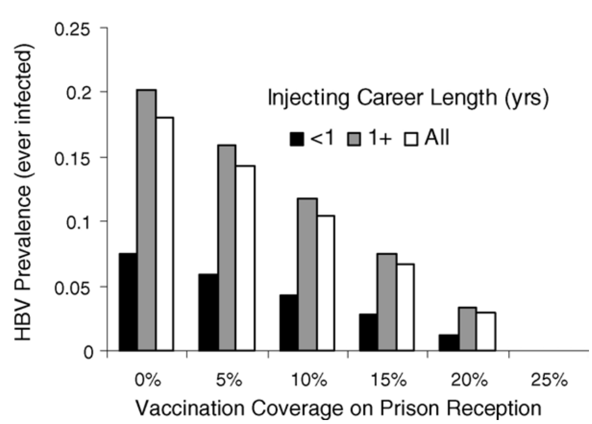

Fig. 3. The relationship between the vaccination coverage on prison reception and the post-vaccination equilibrium.

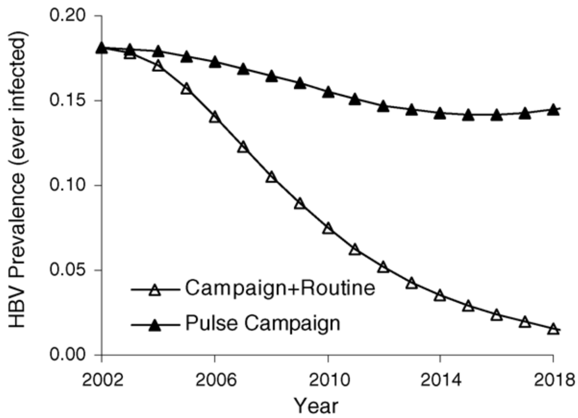

Fig. 4. The impact of alternative campaign vaccination scenarios on the prevalence of HBV within the IDU population over time.

2% within 15 years. The impact of administering a vaccination campaign every three years from 2003 until 2009 can also be seen in Fig. 4. It can be seen that while this strategy does have a positive effect on HBV prevalence, if this is not sustained, then 7 years after the final pulse vaccination the HBV prevalence once again begins to rise.

3.5. Sensitivity analysis

The effect on the baseline vaccination scenario of varying the estimated force of infection in new initiates and experienced IDUs is shown in Fig. 5. It can be seen that alternative values of the FOI have the potential to have a substantial effect on the HBV incidence estimates obtained from the model.

The impact of varying the proportional mixing assumption is shown in Fig. 6. It can be seen either assuming that the rates of mixing are dominated by experienced IDUs (Mixing 1) or assuming that there is no mixing between new initiates and experienced IDUs (Mixing 2) has very little impact on the estimated number of acute cases of HBV in the IDU population.

4. Discussion

Using a deterministic model to describe the epidemiology of HBV within the IDU population, the work here shows the potential impact of the HBV vaccination programme in prisons on the incidence and prevalence of HBV in the IDU population in England and Wales. Over a range of vaccination scenarios the model shows that increased coverage of HBV vaccination on prison reception can have a substantial effect on the incidence of HBV within the IDU population over time. Indeed, the base case model (that assumes that the vaccination coverage on prison reception is 5% in 2002, 10% in 2003 and then increases linearly up to 50% of prison receptions being vaccinated by 2006) predicts that the incidence of HBV in IDUs might be reduced by almost 80% in 12 years from over 1200 acute cases down to less than 300.

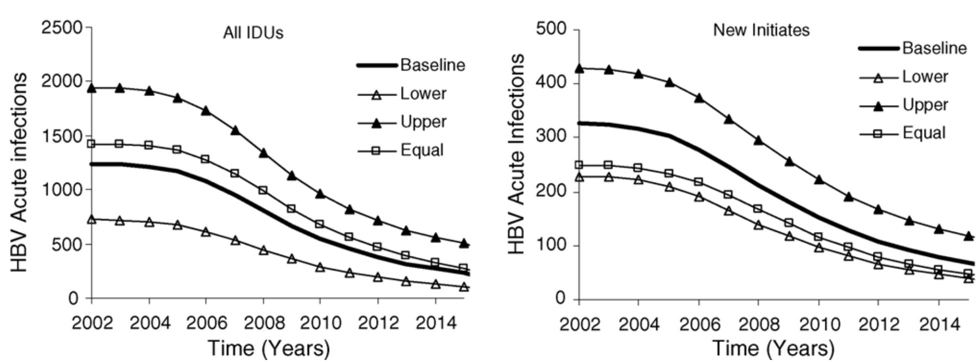

Fig. 5. The estimated annual number of acute infections of HBV in the IDU population with variations in the estimated FOI.

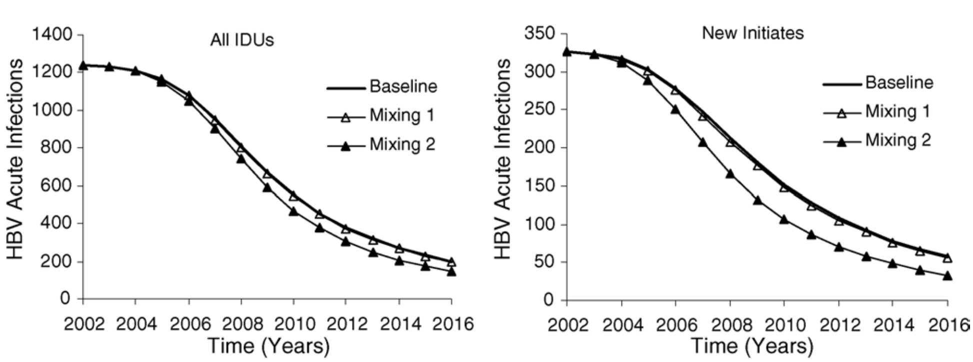

Fig. 6. The estimated annual number of acute cases in the IDU population with variations in estimations of the transmission coefficients.

It has been assumed that the IDU population can be divided into two groups, those new initiates with an injecting career length of less than 1 year, and experienced IDUs with an injecting career length of greater than 1 year. This finding can be justified when considering the FOI estimates [10] which are substantially higher in new initiates compared to more experienced IDUs. While it is acknowledged that this is almost certainly an over simplification of the process by which IDUs interact, its simplicity makes model parameterisation easier based on data currently available. However, it has been shown that there may also be individual heterogeneity of risk behaviour within the IDU population that is independent of injecting career length [10]. Although the model structure proposed here does not allow for this possibility, future work may involve the modification of the model structure by assigning IDUs based on their injecting behaviour to be either high-risk or low-risk from blood-borne viruses.

From a previous modelling study [10] no statistically significant variation in the FOI over time in IDUs was detected from 1999 to 2002 when fitting a model to HBV prevalence data [2] of IDUs in England and Wales. It has therefore been assumed that there is no variation in the FOI through time prior to the introduction of prison vaccination. However, the impact of using a dynamic model in which the FOI is not fixed [13] inevitably results in a decrease in the FOI over time when vaccination is introduced.

The rates that IDUs are vaccinated were calculated from results obtained from a model of the HBV vaccination programme in prisons [4]. This model describes the flow of IDUs through prison, and estimates the number of IDUs that are vaccinated under a range of alternative vaccination scenarios. This model relies heavily on data obtained from a prison survey conducted in 1997 [3] and so any changes in the characteristics of the imprisoned IDU population that have occurred since 1997 may not be adequately represented in the model. However, surveys of sufficient size to draw conclusions about the offending characteristics across the whole of the IDU population in England and Wales are logistically difficult to implement and none have been undertaken since 1997.

As has been shown during the sensitivity analysis of the model of the HBV vaccination programme in prisons [4] the estimated size of the IDU population has a large impact on the estimated proportion of the IDU population that may be vaccinated on prison reception. A larger IDU population results in a smaller proportion of IDUs being exposed to vaccination on prison reception and this will inevitably have less of an impact on HBV transmission within the IDU population. Results obtained here based on an assumed IDU population size of 160,000 provide estimates of the number of acute cases and HBV prevalence within the IDU population that can be broadly validated by data [2,14] (see below), however more work must be done to estimate the size of this hard to reach population.

Over a range of vaccination scenarios the results from this model have shown that an increase in the vaccination coverage on prison reception results in a reduction in the number of acute cases of HBV in both new initiates to injecting and in experienced IDUs over time. Allowing for community vaccination the total number of acute HBV infections in 2002 in the IDU population in England and Wales was estimated from the model to be approximately 1200; this includes all acute cases of HBV both asymptomatic and symptomatic. To verify this result it can be compared to the number of acute cases of HBV in England and Wales with a risk factor associated with injecting drug use as reported to the Health Protection Agency in 2002 [14], this was found to be 193. However, after adjusting for under-reporting [15] and asymptomatic infection [1], the annual number of acute infections is estimated at 1100 cases, suggesting that the model is providing a reasonable estimation of the number of acute HBV infections in the IDU population in England and Wales.

The vaccination scenarios here were estimated in 2004 when results from the model of the prison vaccination programme in prisons were being obtained [4]. These same scenarios have been implemented here to show how they would impact on HBV transmission in the IDU population in England and Wales. If the vaccination coverage on prison reception described by these scenarios has been over estimated then the future impact on HBV transmission within the IDU population may be less than shown here. Indeed from January to December 2003 vaccination coverage across prisons in England and Wales remained low [16] this being partially due to the small proportion of prisons participating in the vaccination programme. However, the hypothetical vaccination scenarios investigated here do show that relatively low vaccination coverage on prison reception might ultimately result in HBV elimination in the IDU population (Fig. 3), while even the scenario that describes the lowest vaccination coverage on prison reception (Scenario A) has a substantial effect on acute HBV infection (Fig. 1).

The impact on the HBV prevalence within the IDU population over a range of hypothetical vaccination scenarios was also investigated. It was found that targeting the 18–29 age group had the greatest impact on HBV prevalence, compared to the 15–17 age group and 30+ age groups. Although targeting age groups of different sizes will inevitably favour the larger age groups it is likely that this result is due to the majority of IDUs being aged from 18 to 29. However, the model of the HBV vaccination programme in prisons assumes that the likelihood of starting injecting is the same irrespective of imprisonment status, whereas it is likely that persons that have previously been imprisoned are more likely to start injecting than those that have not, which suggests that the impact on HBV prevalence of vaccinating young prisoners may be underrepresented here.

The equilibrium scenarios were examined to see what levels of constant vaccination coverage on prison reception would result in the HBV prevalence reducing to zero. It was found that under base case assumptions a vaccination rate of between 20 and 25% would ultimately result in the HBV prevalence in the IDU population reducing to zero. While this result is interesting it is subject to a number of caveats. It is assumed both that the characteristics of the IDU population both inside and outside prison and the characteristics of the prison population are reasonably approximated here and remain constant over the same time period, which is unlikely particularly given that equilibrium is not reached for thousands of years. While these are important caveats and should not be overlooked it does show that prison vaccination on reception has the potential to impact upon HBV prevalence within the IDU population in a substantial way.

The assumption that there is proportional mixing between new initiates and experienced IDUs was tested during the sensitivity analysis. It was assumed that the rate that the two groups interact was dominated by experienced IDUs, and alternatively it was assumed that there was no mixing between the groups. In each case it was found that the model results are not sensitive to these changes.

As has already been discussed the FOI estimates were taken from a previous analysis of IDUs in contact with services [4], to test their impact on model results alternative plausible FOI estimates were substituted [4]. It was found that the force of infection estimates have a major impact on the results obtained from the model particularly when the FOI is estimated to be the same in both groups suggesting that future work should be aimed at verifying these parameter values. It was assumed that the FOI estimates applied here were the same both inside and outside prison, while this is a bold assumption, obtaining data from which prison and community specific FOI estimates can be estimated will always prove problematic. As better FOI estimates become available that can distinguish the risk of infection both inside and outside prison, these can be incorporated into the model.

To verify whether the results obtained from this model are a reasonable estimation of the impact of the HBV vaccination programme in prisons on the transmission of HBV in the IDU population, reports of acute cases of HBV that are reported to the HPA in future years can be compared to the results presented here. Allowing for asymptomatic infection and underreporting, it will then be possible to verify whether the estimated impact of the HBV vaccination programme in prisons on HBV transmission in the IDU population in England and Wales is correct.

An important caveat within this work is that HBV transmission by non-IDUs has not been explored within this model. While it is likely that HBV will never be eradicated in the IDU population due to transmission from non-IDUs to IDUs, prison vaccination will inevitably capture many non-IDUs that have increased risk factors from HBV infection, (e.g. sex workers) and this will have a positive impact on HBV transmission within the overall population of England and Wales.

A previous U.S. study has suggested that HBV vaccination on prison reception may be cost effective [17], however this study is limited as it is specific to prisons in the U.S. and does not consider the on-going impact over time of prison based vaccination on HBV transmission. Nevertheless future work may consider the cost-effectiveness of alternative HBV vaccination scenarios (e.g. pulse versus continuous vaccination) that target prisoners in England and Wales and this may inform as to the best way to deliver the programme. Future work may also consider more complicated models that better represent the characteristics of the IDU population; these may incorporate the number of injections, the number of partners, and may include the possibility of interaction between buddy and stranger users [18]. However, more complex models will rely on detailed data with which to parameterise them and this may not be readily available.

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Appendix A

A.1. Mathematical structure

The differential equations for the deterministic model are as follows:

$$\frac{\mathrm{d}S_0}{\mathrm{d}t} = \alpha - \mu_0 S_0 - \lambda_0(t) S_0 - v_0(t) S_0 \tag{1}$$

$$\frac{\mathrm{d}S_i}{\mathrm{d}t} = -\mu_i S_i - \lambda_i(t) S_i - v_i(t) S_i, \text{ where } i = 1, 2, 3, \text{ etc.} \tag{2}$$

$$\frac{\mathrm{d}L_i}{\mathrm{d}t} = \lambda_i(t) S_i - \mu_i L_i - \sigma L_i \tag{3}$$

$$\frac{\mathrm{d}A_i}{\mathrm{d}t} = \sigma L_i - \mu_i A_i - \gamma_1 A_i \tag{4}$$

$$\frac{\mathrm{d}C_i}{\mathrm{d}t} = p\gamma_1 A_i - \mu_i C_i - \gamma_2 C_i \tag{5}$$

$$\frac{\mathrm{d}R_i}{\mathrm{d}t} = (1-p)\gamma_1 A_i + \gamma_2 C_i - \mu_i R_i \tag{6}$$

$$\frac{\mathrm{d}V_i}{\mathrm{d}t} = v_i(t) S_i - \mu_i V_i \tag{7}$$

where i represents the injecting career length class, σ represents the rate at which latents become infectious, and γ_1 and γ_2 are the recovery rates of acute infections and carriers, respectively. (Note that $1/\sigma$, $1/\gamma_1$ and $1/\gamma_2$ are, respectively, the average duration of the latent, acute and carrier states.) The number of new IDUs that start injecting each year is represented by α. The probability that an individual fails to clear an acute infection and develops the carrier state is represented by p.

The rate at which with injecting career length i individuals leave the IDU population is denoted μ_i (dependent of injecting career length and time). The vaccination rate is denoted as $v_i(t)$. The FOI $\lambda_i(t)$, also depends on injecting career length and time. The FOI acting on susceptibles with an injecting career length of i at time t is assumed to be:

$$\lambda_i(t) = \sum_{j=0}^{j=\rho} \beta_{ij}[A(t)_j + \delta C(t)_j] \quad (8)$$

where β_{ij} describes the transmission coefficient between susceptibles of injecting career length i and infectious individuals (both carriers and acute infections) of injecting career length j, and δ represents the relative infectiousness of carriers compared with acute infections[7] and ρ is the number of injecting career length classes. The initial conditions $X_i(^*)$, $L_i(^*)$, $A_i(^*)$, $C_i(^*)$, $R_i(^*)$, and $V_i(^*)$ are the numbers of IDUs of injecting career length i, in each state at time equal to 0 and are taken to be the equilibrium number of susceptibles, latents, acutes, carriers, immunes, and vaccinated prior to the introduction of prison vaccination (but with community vaccination). This was found by setting the time derivatives to zero and solving the resulting set of simultaneous equations to yield the equilibrium numbers of susceptibles, latents and so on.

A.2. Removal rates

The age-specific removal rates are converted to be injecting career length specific via the following method:

n_{ki} is defined as the total number of IDUs with injecting career length i of age k and is equal to:

$$n_{ki} = \alpha f_{k-i} \prod_{j=0}^{j=i-1} (1 - \omega_{k-j}) \quad (9)$$

where f_k is the proportion of IDUs starting injecting at age k, and ω_k is the age dependent stop rate.

The total number of IDUs with an injecting career length i, N_i is:

$$N_i = \sum_{k=15}^{k=75} n_{ki} \quad (10)$$

and

$$\mu_i = -\ln \frac{N_i}{N_{i+1}} \quad (11)$$

A.3. The force of infection and transmission coefficients

As the FOI is different for new initiates to injecting (injecting career length <1 year) and experienced IDUs (injecting career length 1+ years). The FOI within each of these discrete injecting career length groups is described by the following two equations:

$$\lambda_1 = \beta_{11} \sum_{i=0}^{i=1} (A_i + \delta C_i) + \beta_{12} \sum_{i=1}^{i=\infty} (A_i + \delta C_i) \quad (12)$$

$$\lambda_2 = \beta_{21} \sum_{i=0}^{i=1} (A_i + \delta C_i) + \beta_{22} \sum_{i=1}^{i=\infty} (A_i + \delta C_i) \quad (13)$$

where

λ_1 is the FOI for those IDUs with an injecting career length of <1 years, λ_2 is the FOI for those IDUs with an injecting career length of 1+ years.

A.4. Proportional mixing

For proportional mixing β_{ij} is defined as:

$$\beta_{ij} = \frac{d_i d_j N_j}{d_i N_i + d_j N_j} \quad (14)$$

where d_i is the effective contact rate for individuals in group i, and N_i is the number of individuals in group i.

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