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Combined treatment and prevention strategies for hepatitis C virus elimination in the prisons in New South Wales: a modelling study

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ABSTRACT

Background and aims Australia is currently on track to meet the World Health Organization (WHO) global hepatitis C virus (HCV) elimination goals by 2030, reflecting universal subsidized access to testing and direct-acting antiviral (DAA) treatment. In New South Wales, DAA treatment in prisons has scaled-up substantially, with 1000 prisoners treated in 2017. However, HCV prevalence and incidence in this setting is high, which could undermine elimination efforts. This study aimed to test the preventative effects of DAA treatment scale-up, opiate substitution treatment (OST) and needle and syringe programme (NSP) strategies for prisons. **Design** Modelling study using an individual-based mathematical model of a typical prison setting. The model was calibrated against Australian epidemiological data sets and executed in-prison events for each individual daily, including movements between prisons, changes in risk behaviour and uptake of prevention measures such as OST and NSP, as well as DAA treatment. Scenarios were projected from 2018 to 2030. **Setting** New South Wales prisons. **Participants** New South Wales prisoners. **Measurements** Variables including prison populations, prevalence and incidence rate were calculated. Prisoners were described by demographic characteristics, HCV infection history, risk behaviours and accessing treatment and prevention measures in varied security settings. **Findings** Increasing the number of prisoners treated for HCV to 2000 annually was projected to reduce the HCV incidence rate to 8.69 [95% confidence interval (CI) = 8.17, 9.20] per 100 person-years (100 p.y.). Combined treatment and prevention strategies were necessary to reduce the projected incidence rate to 5.22 (95% CI = 5.13, 5.52) per 100 p.y. Considering the expected reductions in the prevalence of chronic HCV in the Australian community, incidence rate was predicted to drop to 0.93 (95% CI = 0.92, 0.98) per 100 p.y. by 2030. **Conclusions** This model, which simulates prison scenarios to inform Australia's national hepatitis C virus elimination efforts, suggests that continued direct-acting antiviral (coverage in the community combined with a moderate increase of direct-acting antiviral treatments in prisons, and introduction of improved harm reduction via opiate substitution treatment and/or needle and syringe programmes, makes hepatitis C virus elimination feasible in Australian prisons.

Keywords Direct-acting antiviral, HCV, hepatitis C virus, modelling, needle and syringe exchange programme, prevention, prisons, treatment.

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INTRODUCTION

Injecting drug use (IDU) with sharing of injecting equipment is the major route of hepatitis C virus (HCV) transmission. Accordingly, people who inject drugs (PWID) are the premier risk group for HCV infection [1]. Due to the illegal nature of IDU, PWID are commonly incarcerated, with an estimated 1.5 million individuals with chronic HCV infection housed in correctional centres world-wide (15% of all prisoners) [2]. In Australian prisons (this term

is used to include both gaols and prisons), the prevalence of chronic HCV is approximately 20% [3], and the ongoing HCV transmission rate is high (10–15% per annum among PWID) [4]. In 2016, Australia's prevalent prisoner population reached 38 845, 92% of whom were men, distributed across approximately 100 correctional centres [5]. Approximately 70 000 people were cycled through Australian prisons in 2016 [6], and almost 50% reported IDU [7]. These characteristics of IDU and HCV prevalence in Australian prisons are representative of many prisons across the globe, especially in high-income countries [2].

While incarceration may reduce or halt injecting and sharing activity in some PWID, imprisonment has also been reported to increase IDU behaviour in others, and even to mark the initiation into IDU [8,9]. In-prison IDU is associated with a high probability of sharing, as injection devices are sparse and heavily re-used [8]. There are very few prison-based needle and syringe programmes (NSP) world-wide (none in Australia), thereby driving repeated use of IDU paraphernalia [8,10]. In addition, the other key HCV prevention strategy in the community—opiate substitution treatment (OST), which is variably available [11]—has not been associated with reduced transmission risk in this setting [4]. The per injecting event probability of HCV transmission in Australian prisons has been estimated to be 0.57% [12].

Recently, the introduction of direct-acting antiviral (DAA) treatment for chronic HCV has provided simple, pan-genotypical, short-duration (8–12-week) regimens with cure rates above 90% [13]. With universal subsidized access both to testing for HCV antibodies and RNA, and to DAA treatments, Australia is on track towards meeting the World Health Organization (WHO) goal of elimination of HCV as a public health threat by 2030 [14], including key targets compared to 2015 levels of 80% decline in incident infections, treatment provision for 80% of those infected and a reduction in HCV-related mortality of 65% [15]. Importantly, there are no restrictions in Australia on who can access treatment regardless of how they acquired their infection or disease stage, and there is specific provision made for access for prisoners [14]. In the first 12 months of DAA access in Australia, prisoners accounted for approximately 6% of the 32 550 individuals treated nationally [16].

In this study, an individual-based mathematical model representing a typical prison setting in Australia was developed to explore the dynamics of HCV transmission in relation to HCV treatment and prevention programmes. The model includes differing security classifications, and also accounts for movements between prison centres and between prison centres and the community, as these impact upon inmate interactions and hence HCV transmissions [17]. The model was calibrated to match epidemiological data collected in the Australian prisons, particularly including data from the most populous state, New South Wales (NSW). The calibrated model was primarily used to perform *in-silico* testing of DAA, OST and NSP provision in the prisons. The epidemiological impacts of various future combination scenarios were assessed.

METHODS

This individual-based model was developed using C++, based on an existing model of HIV transmission [18]. It describes the typical prison setting in Australia, including security classifications designated as individual prison locations (minimum, medium and maximum), demographic characteristics and risk behaviour characteristics (Fig. 1). The total prisoner population was simulated based on the flux of individuals newly incarcerated from the community, released back to the community and transferred between security classifications. Incarcerated individuals were represented as individual agents described by age, Indigenous status, risk group, prison location, liver disease stage, time of infection, re-infection status and OST, NSP and DAA treatment uptake (Fig. 1). Nine risk groups referring to an individual's IDU, injecting frequency, opioid use and IDU sharing behaviours were considered (Supporting information, Table S1). For individuals with chronic HCV, liver disease stage, time and place of infection were modelled. Non-HCV-related liver disease was not considered.

The model was simulated on a time-scale of 1 day, with individuals probabilistically experiencing up to 23 events per day. These events related to: movement between prison locations, release to community, death, natural clearance of HCV, transition between risk groups, sharing injecting equipment, liver disease stage progression and participation in HCV treatment and prevention programmes. Parameters used by the model to perform simulations and execute events are listed in Table 1, and further described in the Supporting information. Event implementation, as well as the detailed algorithm, is further described in Supporting information, section II, with the open access code for the model available online [19]. To account for stochasticity in the model, a set of 10 simulations were produced by sampling from the parameter distributions and running the model on each corresponding set of parameters. Our results were obtained by taking the mean and 95% confidence interval (CI) of the outputs from these 10 simulations. We found that 10 simulations were sufficient to produce robust results (see Supporting information, section X).

MODEL CALIBRATION

The model was calibrated against observed prisoner population, HCV prevalence and HCV incidence rate, as

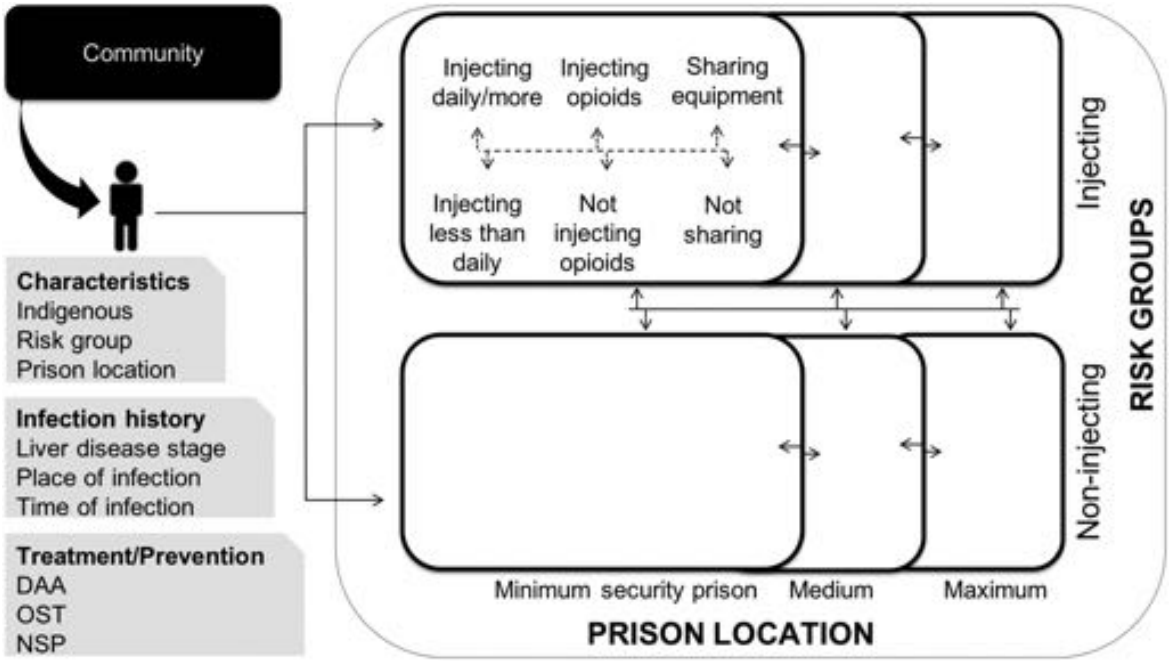

Figure 1 The structure of the prisons model and its individual agents. Each prisoner is represented as an individual agent described by a set of characteristics, hepatitis C virus (HCV) infection history and enrolment into treatment and prevention strategies. The model implemented prison dynamics via moving individual agents between with risk groups and security locations, and executing events based on parameters collected from the published literature

Table 1 Parameters[a,b] used in the model.

Parameter	*Distribution*	*Reference*
Number of individuals incarcerated per day	Exponential[c] (μ^{d} = 40.26[e]); an annual increase of 0.01[e] was applied from 2006 to 2014, 0.2[e] from 2015 to 2017 and 0.02[e] from 2018 onwards	(Refs 4,11–19 in Supporting information)
Sharing of injecting equipment		
Injecting less than daily	Fixed value[f] (x = 0.144[e])	[8]
Injecting daily or more	Fixed value[f] (x = 0.26[e])	[8]
Death in prison	Uniform[f] (a^{g} = 4.23e-06; b^{h} = 5.35e-06)	[34]
HCV progression rates		
F0→F1	Uniform[f] (a = 1.6e-04; b = 7.7e-04)	[35]
F1→F2	Uniform[f] (a = 1.8e-04; b =3.0e-04)	[35]
F2→F3	Uniform[f] (a = 1.3e-04; b = 4.0e-04)	[35]
F3→F4	Uniform[f] (a = 1.5e-04; b = 8.7e-04)	[35]
Spontaneous clearance of HCV		
HCV RNA+[i] <=180 days	Exponential[f] (μ = 0.5e-04)	[36]
HCV RNA+ > 180 days and < 360 days	Exponential[f] (μ = 0.2e-04)	[36]
> 360 days	Fixed value[f] (x = 0)	[36]

[a]Parameter values are shown as daily rates. [b]Parameters for assigning initial characteristics, movement between locations, and risk behaviours are listed in Supporting information, Table S4; [c]drawn per simulation day; [d]mean value; [e]optimized value for calibration; [f]drawn for every prisoner per simulation day; [g]minimum value; [h]jaximum value; [i]HCV RNA+ indicates chronic hepatitis C virus (HCV) infection.

reported by Corrective Services NSW, Justice Health and the HITS-p and SToP-c studies [3,20,21] (see Supporting information, section IX). The prisoner population was projected to continually grow during the next decade, in line with increasing trends in incarceration in Australia due to an increase in offenders remanded in custody and increases in prisoners arrested for sexual, drug and other procedure offences (Fig. 2, Supporting information, Table S11) [22]. The incidence rate among PWID was calculated as the number of new cases in prison divided by the total

number of PWID. This was calculated to reflect the dynamic nature of injecting drug use in the prison setting. For prevalence, HCV antibody prevalence was calculated as the number of individuals with HCV antibody-positive status divided by the total prisoner population. HCV antibody prevalence among incarcerated PWID was also calculated as the number of individuals with HCV antibody-positive status divided by the total number of PWID.

The initial set of model parameters obtained from literature were optimized using a grid search method until observed data were matched (see Supporting information, section IX). In parallel, this process revealed the sensitivity of the model in relation to each parameter.

PROJECTION SCENARIOS

The model was used to project HCV transmissions in the prisons up to 2030, using the strategies listed in Table 2 simulated under the various scenarios listed in Table 3. The *status quo* assumed continuation of the current situation in the NSW prisons: a starting total prisoner population in 2017 of 14 683, including 7862 PWID, 3847 of whom were actively injecting at any one time (as reported [3,21]); 1400 individuals receiving OST at any one time from 2006 onwards [3]; and 200 DAA treatments per year from 2014 to 2016, 700 in 2016 and 1000 in 2017, again reflecting the actual scale-up of DAA treatment in the NSW prisons. The impact of further scale-up of DAA treatment provision, improved

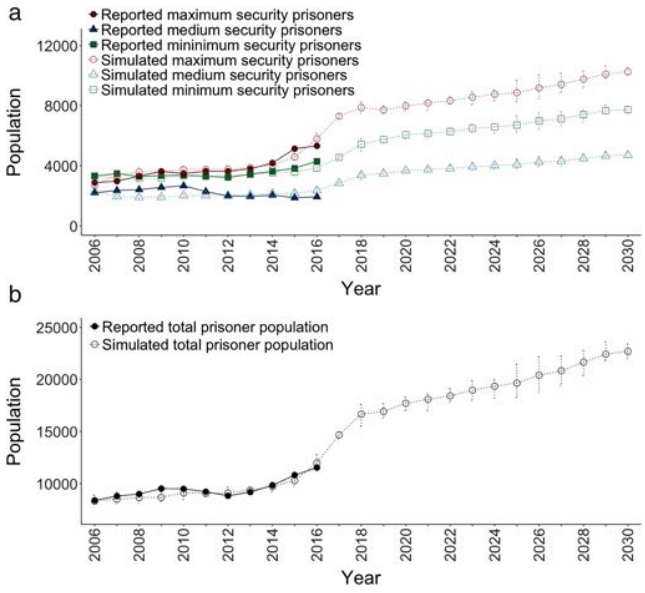

Figure 2 Projected prisoner population from 2006 to 2030. (a) The breakdown of the actual NSW prisoner population according to security classification and the projected trends in the model. (b) The actual total NSW prisoner population and the projected trends in the model. Plots show the mean of 10 simulations with variation represented as error bars. The actual prisoner population reported by Corrective Services NSW (Supporting information). For the corresponding values, see Supporting information, Table S11 [Colour figure can be viewed at wileyonlinelibrary.com]

Table 2 Implemented effects of treatment and prevention strategies in the model.

Strategy	*Implemented effect*	*Distribution*	*Reference*
DAA	Chance of clearing HCV increased by 8% per week over 12 weeks resulting in an approximately 95% chance of clearing HCV within 12 weeks	Fixed value[a] (x = 0.08) multiplied by duration of infection in weeks	[37]
OST	55–75% reduction in sharing of injecting equipment	Uniform[a] (a^b = 0.55; b^c = 0.75)	[38]
NSP	10% reduction in sharing of injecting equipment	Fixed value[a] (x = 0.1)	[39]
	23% reduction in sharing of injecting equipment	Fixed value[a] (x = 0.23)	[39]
Reduction in community HCV prevalence	Annual (2018–30) percentage reduction in new incarcerations who are HCV RNA+[d] based on pessimistic estimates in Australia due to DAA rollout*	Fixed value[a] (varies per year; see Supporting information, Table S15)	[23]
	annual (2018–30) percentage reduction in new incarcerations who are HCV RNA+[d] based on optimistic estimates in Australia due to DAA rollout*	Fixed value[a] (varies per year; see Supporting information, Table S15)	[23]

[a]Drawn for every prisoner per simulation day; [b]minimum value; [c]maximum value; [d]chronic HCV infection. *Derived from NSW estimates and projections [23]. HCV = hepatitis C virus; DAA = direct-acting antiviral; NSP = needle and syringe programme; OST = opiate substitution treatment.

Table 3 Strategies and scenarios considered for onward projections.

Strategy	*Scenario name*	*Description*
Status quo		Maintained n = 1000 DAA treatments per year from 2018 and n = 1400 OST places at any one time. No NSP was provided and annual population growth was assumed.
DAA	Pessimistic scenario	Reduced DAA treatments to n = 0 per year from 2018 and maintained n = 1400 OST places at any one time
	Optimistic scenario	Increased DAA treatments to n = 2000 per year from 2018 and maintained n = 1400 OST places at any one time
OST	Intermediate scenario	Improved OST provision equal to n = 1400 OST places at any one time
	Optimistic scenario	Improved OST provision to all opioid users at any one time from 2018
NSP	Intermediate scenario	NSP distribution to all PWID with 10% reduction in sharing behaviour from 2018
	Optimistic scenario	NSP distribution to all PWID with 25% reduction in sharing behaviour from 2018
Reduction in community HCV prevalence	Intermediate scenario	Assumed annual reduction in community chronic HCV prevalence based on pessimistic Australian estimates[b] resulting in reduction of newly incarcerated people who are HCV RNA+[a] by 13%
	Optimistic scenario	Assumed annual reduction in community HCV prevalence based on optimistic Australian estimates[b] resulting in reduction of newly incarcerated people who are HCV RNA+[a] by 37%
Combinatorial	DAA (optimistic) + OST (intermediate)	Combined optimistic DAA scenario and intermediate OST scenario
	DAA (optimistic) + OST (intermediate) + NSP (intermediate)	Combined optimistic DAA scenario, intermediate OST scenario and intermediate NSP scenario
	DAA (optimistic) + reduction (intermediate)	Combined optimistic DAA scenario and intermediate reduction scenario
	DAA (optimistic) + OST (intermediate) + reduction (intermediate)	Combined optimistic DAA scenario, intermediate OST scenario and intermediate reduction scenario
	DAA (optimistic) + OST (intermediate) + NSP (intermediate) + reduction (intermediate)	Combined optimistic DAA scenario, intermediate OST scenario, intermediate NSP scenario and intermediate NSP scenario

[a]Chronic HCV infection. [b]Derived from NSW estimates and projections [23]. HCV = hepatitis C virus; DAA = direct-acting antiviral; NSP = needle and syringe programme; OST = opiate substitution treatment.

access to OST (implying both timely provision upon incarceration and suitable dosing, as well as increased numbers initiated on OST), introduction of NSP and also the expected reduction in community HCV prevalence due to the national DAA treatment rollout, were then tested (Table 2) [23]. Various combined treatment and prevention scenarios were then simulated based on these strategies (Table 3). The implementation of these strategies in the model is further discussed in Supporting information, section XV.

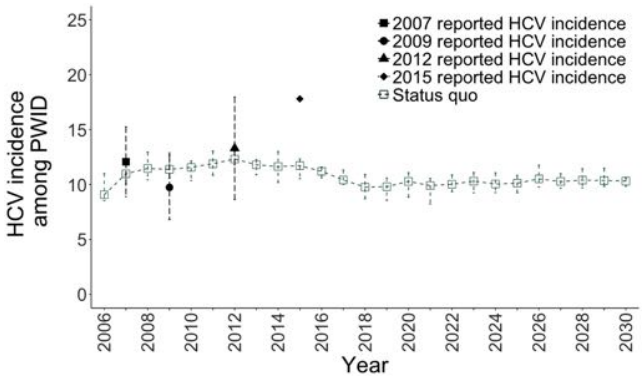

Figure 3 Projected hepatitis C virus (HCV) incidence rate per 100 person-years (p.y.) from 2006 to 2030. Incidence rate was calculated as the number of new cases in prison divided by the total number of incarcerated people who inject drugs (PWID). Plots show the mean of 10 simulations with variation represented as error bars. HCV incidence rates were obtained from the HITS-p and SToP-C studies [20,21]. For the corresponding values, see Supporting information, Table S14 [Colour figure can be viewed at wileyonlinelibrary.com]

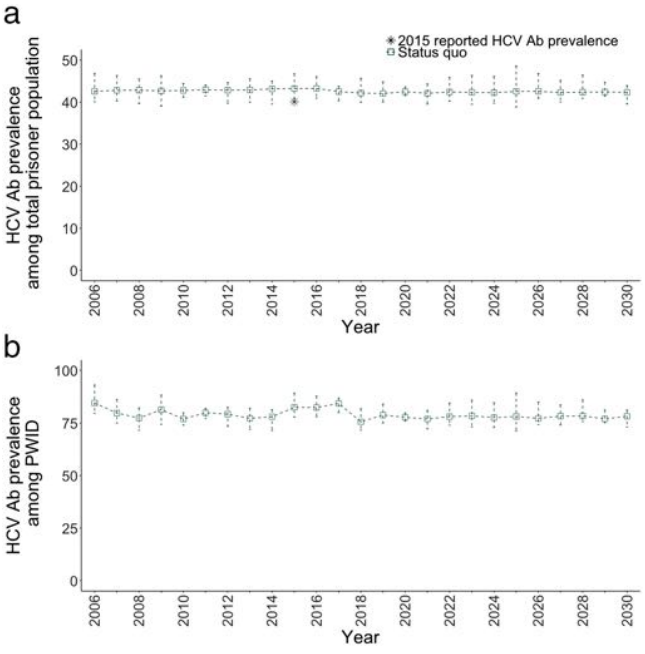

Figure 4 Projected hepatitis C virus (HCV) antibody-positive prevalence in the prisons from 2006 to 2030. (a) The projected HCV antibody prevalence calculated as the number of individuals with HCV antibody-positive status divided by the total prisoner population. (b) The projected HCV antibody prevalence calculated as the number of individuals with HCV antibody-positive status divided by the total number of incarcerated people who inject drugs (PWID). Plots show the mean of 10 simulations with variation represented as error bars. HCV antibody prevalence was obtained from the 2015 Network Patient Health Survey [3]. For the corresponding values, see Supporting information, Table S14 [Colour figure can be viewed at wileyonlinelibrary.com]

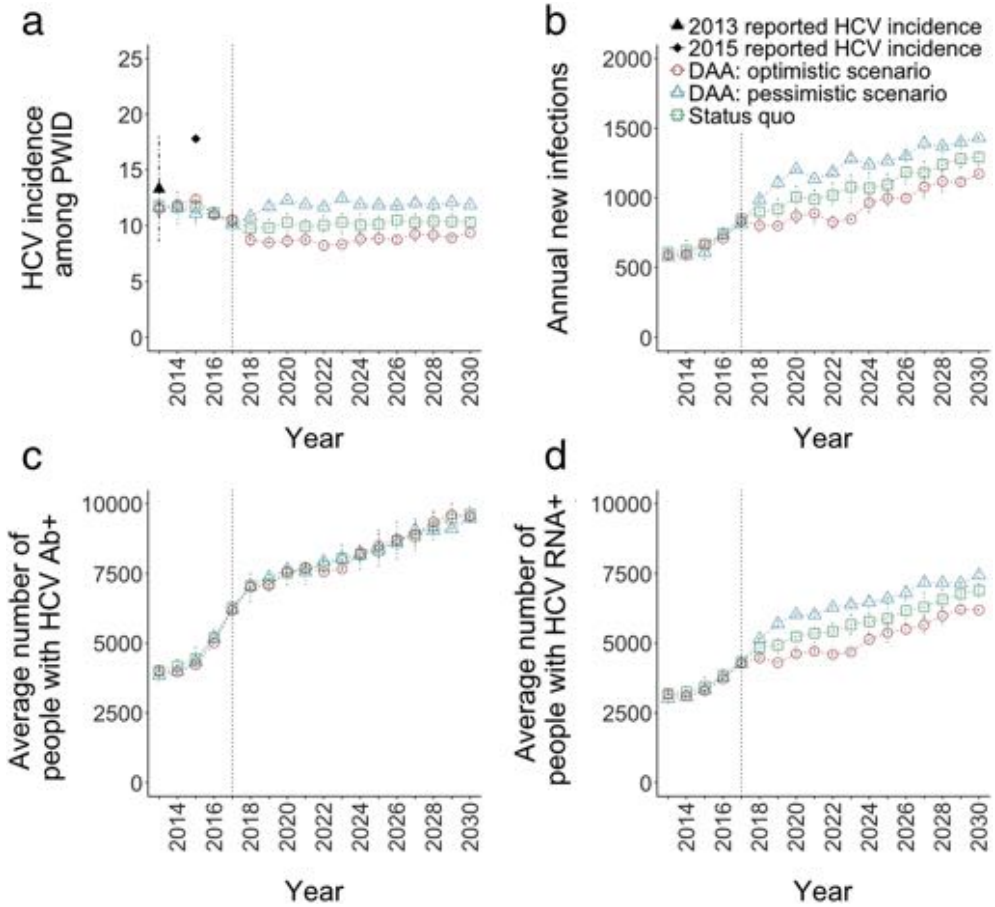

Figure 5 Comparison of simulations under three direct-acting antiviral (DAA) scenarios: (i) *status quo*; (ii) pessimistic scenario; and (iii) optimistic scenario (Table 3). (a) The simulated annual hepatitis C virus (HCV) incidence rate among all incarcerated people who inject drugs (PWID). (b) The number of new infections annually. (c) The average number of people with HCV antibody-positive status. (d) The average number of people with HCV RNA+ status (i.e. viraemia). Plots show the mean of 10 simulations with variation represented as error bars. Actual HCV incidence rates were obtained from the HITS-p and SToP-C studies [20,21]. For the corresponding values, see Supporting information, Tables S16–S19 [Colour figure can be viewed at wileyonlinelibrary.com]

RESULTS

Assuming continuation of the recent *status quo* in treatment and prevention programmes, HCV incidence rate was projected to remain stable over the next decade (Fig. 3, Supporting information, Table S14). Similarly, HCV antibody prevalence among the total prison population was projected to remain high over the next decade (Fig. 4, Supporting information, Table S14).

ASSESSING THE IMPACT OF SCALING-UP DAA TREATMENTS

Increasing DAA treatments to 2000 while maintaining 1400 OST places at any one time from 2018 onwards was projected to reduce the HCV incidence rate by 1.72 percentage points (95% CI = 1.21, 2.24) in the first year (Fig. 5, Supporting information, Table S16). In the scenario that DAA treatments in the prisons is ceased, HCV incidence rate in prisons was projected to increase (Fig. 5, Supporting information, Table S16). In both scenarios, new HCV infections and the number of people with chronic HCV was projected to continue increasing (Fig. 5, Supporting information, Tables S17–S19).

ASSESSING THE IMPACT OF IMPROVING OST PROVISION

Improved access to, and administration of, OST to 1400 prisoners with an assumed reduction of 55–75% in sharing of injecting equipment was projected to reduce HCV incidence rate by 3.24 percentage points (95% CI = 2.59, 3.7) (Fig. 6, Supporting information, Table S16). Moreover, increasing provision of OST to all PWID who report recent injecting of opioids was projected to reduce the HCV incidence rate even further (Fig. 6, Supporting information, Table S16). In both scenarios, new HCV infections were projected to reduce (Fig. 6, Supporting information, Table

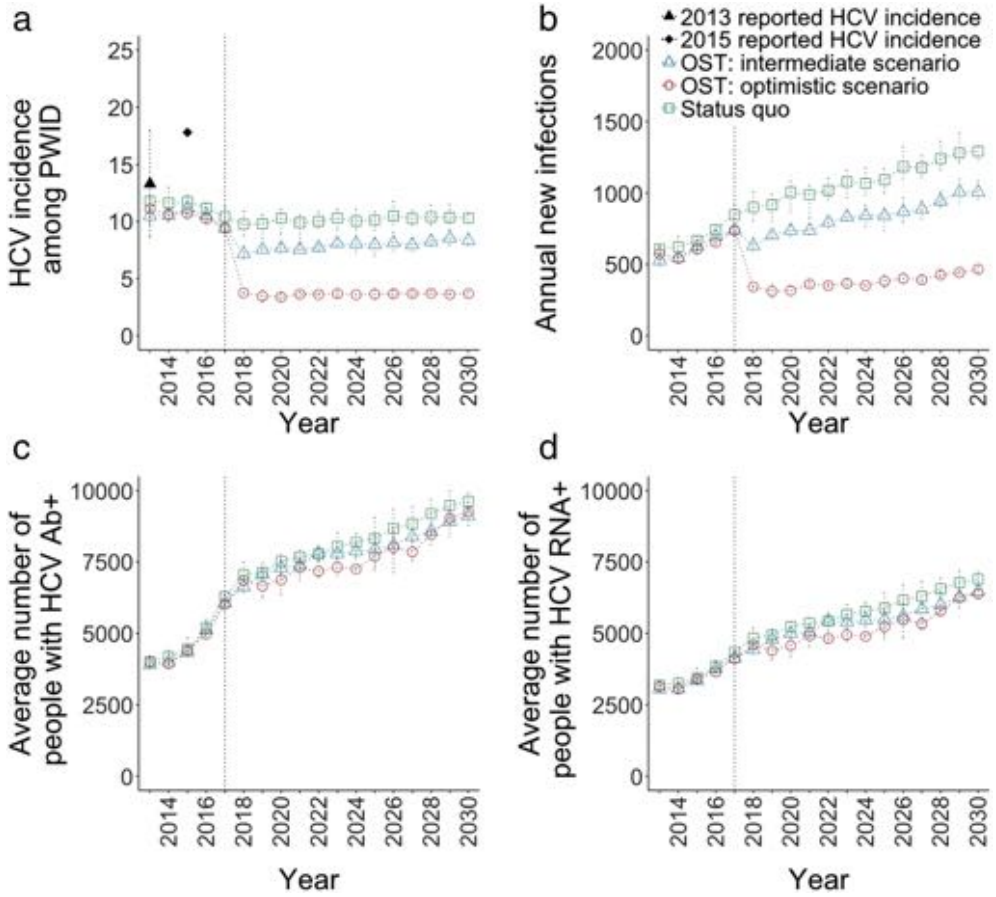

Figure 6 Comparison of simulations under three opiate substitution treatment (OST) scenarios: (i) *status quo*; (ii) intermediate scenario; and (iii) optimistic scenario (Table 3). (a) The simulated annual incidence of hepatitis C virus (HCV) among all incarcerated people who inject drugs (PWID). (b) The number of annual infections. (c) The average number of people with HCV antibody-positive status. (d) The average number of people with HCV RNA+ status. Plots show the mean of 10 simulations with variation represented as error bars. Actual HCV incidence rates were obtained from the HITS-p and SToP-C studies [20,21]. For the corresponding values, see Supporting information, Tables S16–S19 [Colour figure can be viewed at wileyonlinelibrary.com]

S17). Chronic HCV was, however, projected to continue increasing (Fig. 6, Supporting information, Tables S18–S19).

ASSESSING THE IMPACT OF INTRODUCING NSP

Introduction of unrestricted NSP with an assumed 10% reduction in sharing behaviour was projected to reduce the HCV incidence rate by 2.21 percentage points (95% CI = 2.13, 2.74) in the first year (Fig. 7, Supporting information, Table S16). Assuming that a 25% reduction in sharing behaviour associated with unrestricted NSP provision, HCV incidence rate was projected to fall further by 3.87 percentage points (95% CI = 3.71, 4.14) (Fig. 7, Supporting information, Table S16). In both scenarios, new HCV infections were projected to stall initially, but to continue increasing (Fig. 7, Supporting information, Table S17). Chronic HCV was also projected to continue increasing (Fig. 7, Supporting information, Tables S18–S19).

ASSESSING THE IMPACT OF REDUCTIONS IN THE COMMUNITY PREVALENCE OF CHRONIC HCV

Assuming a progressive decrease in the proportion of prison entrants with chronic HCV under pessimistic Australian estimates [23], HCV incidence rate in prisons was projected to fall by 1.36 percentage points (95% CI = 1.24, 1.48) in the first year (Fig. 8, Supporting information, Table S16). Assuming a decrease in the proportion of prison entrants with chronic HCV under optimistic Australian estimates [23], the HCV incidence rate was projected to fall by 0.86 percentage points (95% CI = 0.66, 1.05) in the first year (Fig. 8, Supporting information, Table S16). Using this scenario, HCV in the prisons was projected to be eliminated by 2030 (Fig. 8, Supporting information, Tables S16–S17).

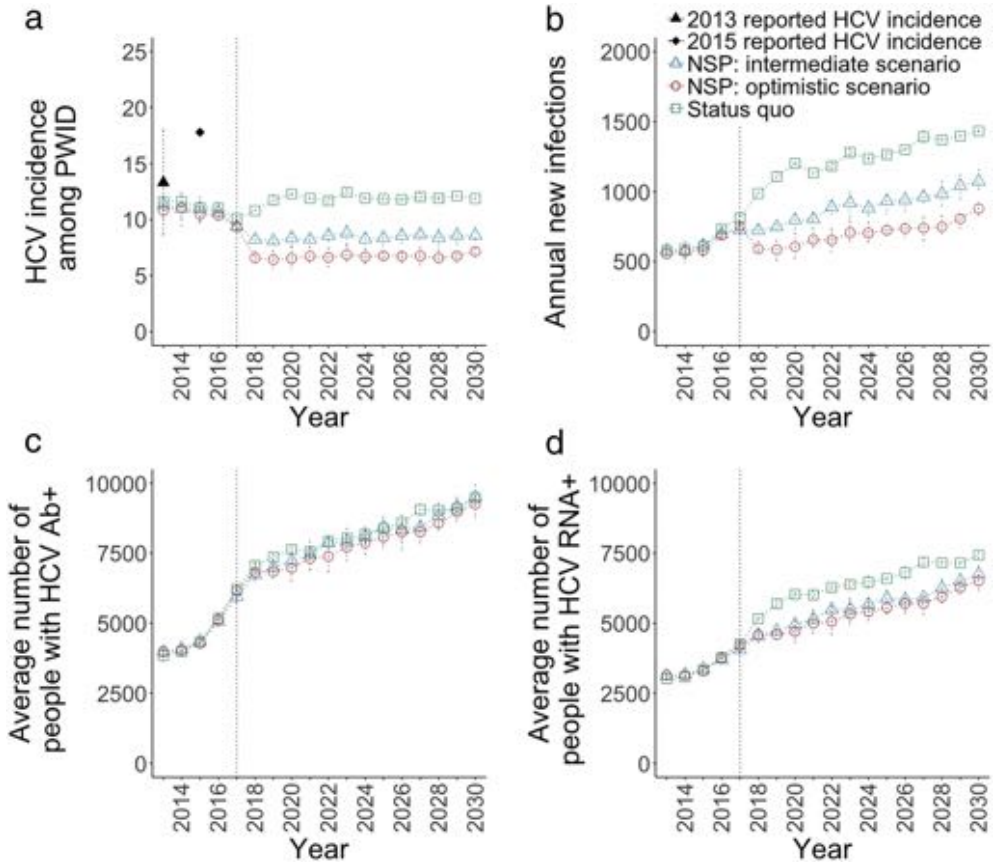

Figure 7 Comparison of simulations under three needle and syringe programmes (NSP) scenarios: (i) *status quo*; (ii) intermediate scenario; and (iii) optimistic scenario (Table 3). (a) The simulated annual incidence of hepatitis C virus (HCV) among all incarcerated people who inject drugs (PWID). (b) The number of annual infections. (c) The average number of prisoners with HCV antibody-positive status. (d) The average number of prisoners with HCV RNA+ status. Plots show the mean of 10 simulations with variation represented as error bars. Actual HCV incidence rates were obtained from the HITS-p and SToP-C studies [20,21]. For the corresponding values, see Supporting information, Tables S16–S19 [Colour figure can be viewed at wileyonlinelibrary.com]

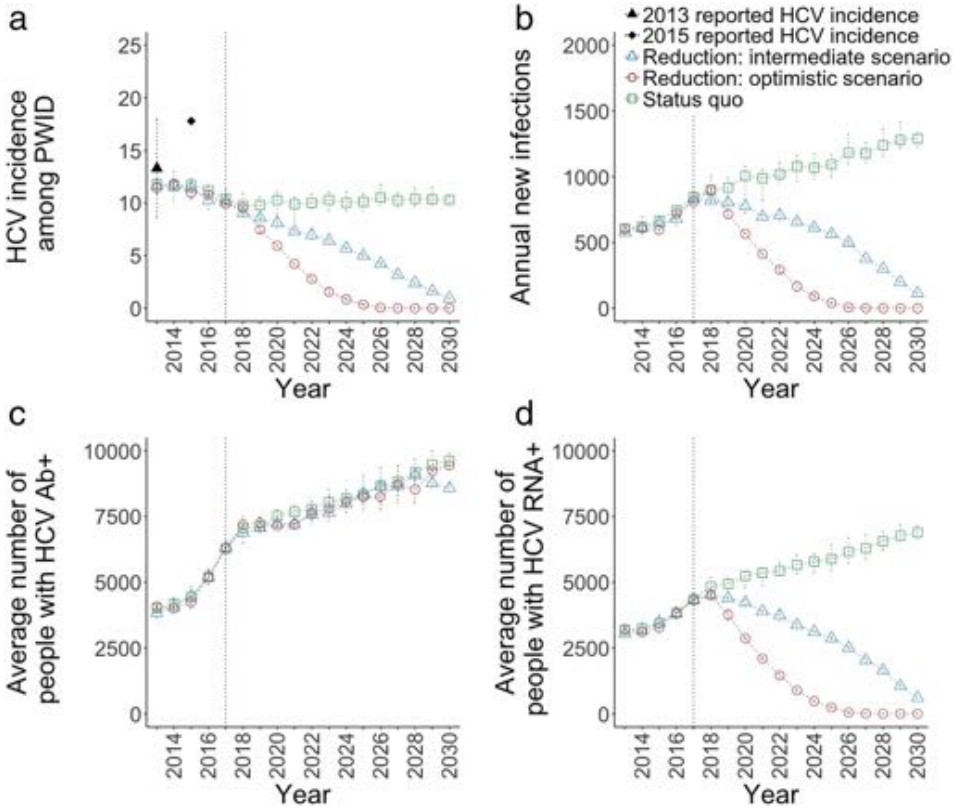

Figure 8 Comparison of simulations under three scenarios of reduction in the chronic hepatitis C virus (HCV) prevalence in the community: (i) *status quo*; (ii) intermediate scenario; and (iii) optimistic scenario (Table 3). (a) The simulated annual incidence of HCV among all incarcerated people who inject drugs (PWID). (b) The number of annual infections. (c) The average number of prisoners with HCV antibody-positive status. (c) The average number of prisoners with HCV RNA+ status. Plots show the mean of 10 simulations with variation represented as error bars. Actual HCV incidence rates were obtained from the HITS-p and SToP-C studies [20,21]. For the corresponding values, see Supporting information, Tables S16–S19 [Colour figure can be viewed at wileyonlinelibrary.com]

ASSESSING THE IMPACT OF COMBINED STRATEGIES

Assuming an increase in DAA treatments to 2000 per year combined with a 55–75% reduction in sharing of injecting equipment due to improved access to OST, the HCV incidence rate was projected to fall by 3.4 percentage points (95% CI = 2.89, 3.91) in the first year (Fig. 9, Table Supporting information, S16). Under this scenario, the number of new HCV infections and those with chronic HCV was projected to continue to increase (Fig. 9, Supporting information, Tables S17–S19).

Assuming an increase in DAA treatments to 2000 per year combined, with a 55–75% reduction in sharing of injecting equipment due to improved access to OST and a further 10% reduction in sharing of injecting equipment due to unrestricted NSP, the HCV incidence rate was projected to fall by 3.95 percentage points (95% CI = 3.41, 4.39) in the first year (Fig. 9, Supporting information, Table S16). Under this scenario, the number of new HCV infections and those with chronic HCV was projected to continue to increase (Fig. 9, Supporting information, Tables S17–S19).

Assuming a decrease in the proportion of prison entrants with chronic HCV under pessimistic Australian estimates combined with 2000 DAA treatments, HCV incidence rate was projected to fall to 0% by 2030 (Fig. 9, Supporting information, Table S16). The same was achieved when assuming a 55–75% reduction in sharing of injecting equipment due to improved access to OST and a further 10% reduction in sharing of injecting equipment due to unrestricted NSP on top of this scenario (Fig. 9, Supporting information, Table S16).

DISCUSSION

An individual-based model representing a typical high-income country prison has been developed and calibrated against epidemiological data sets from the Australian prison sector. This allowed a more detailed approach to modelling of HCV transmissions in the dynamic but enclosed environment with varied security locations, compared to existing prison models [24]. The model allowed for testing of various prison-based prevention strategies, including DAA, OST and NSP provision.

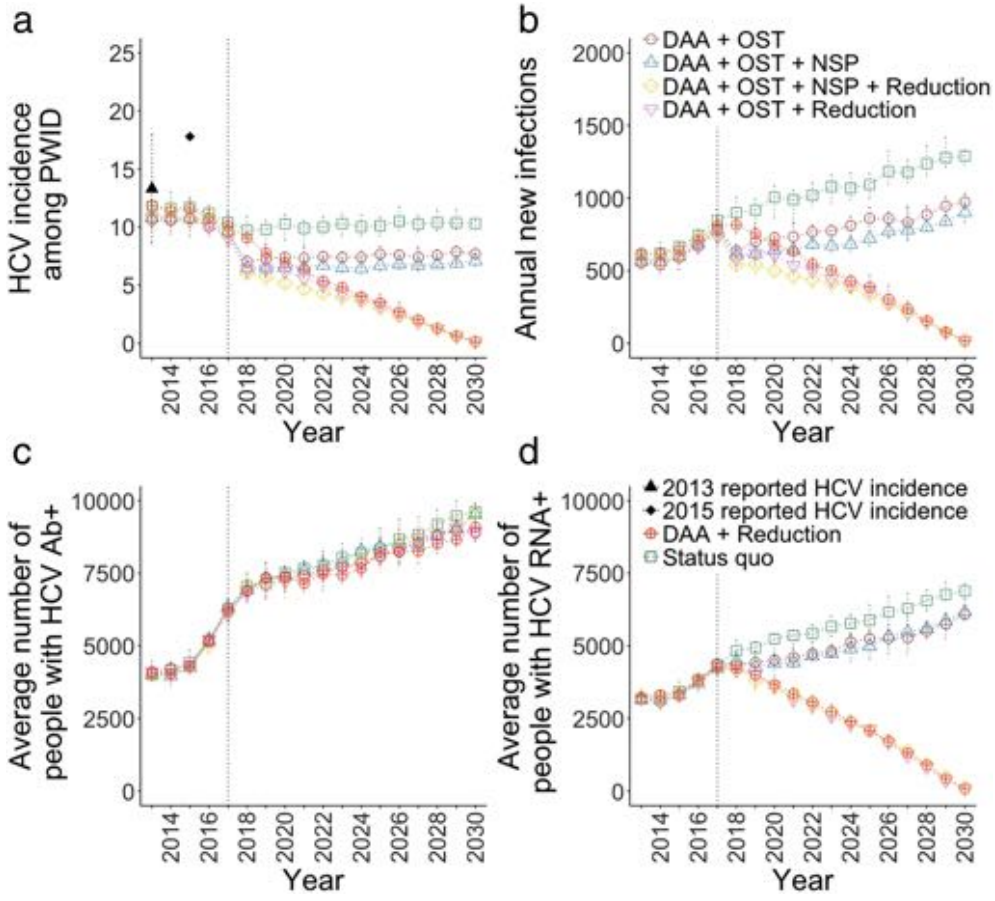

Figure 9 Comparison of simulations under scenarios combining optimistic direct-acting antiviral (DAA), intermediate opiate substitution treatment (OST) and intermediate needle and syringe programmes (NSP) (Table 3). (a) The simulated annual incidence of hepatitis C virus (HCV) among all incarcerated people who inject drugs (PWID). (b) The number of annual infections. (c) The average number of prisoners with HCV antibody-positive status. (c) The average number of prisoners with HCV RNA+ status. Plots show the mean of 10 simulations with variation represented as error bars. Actual HCV incidence rates were obtained from the HITS-p and SToP-C studies [20,21]. For the corresponding values, see Supporting information, Tables S16–S19. [Colour figure can be viewed at wileyonlinelibrary.com]

Model simulations reiterate the high incidence rate of HCV in the NSW prisons that was projected to remain stable up to 2030 if the situation at the end of 2017 continued. The simulated incidence in the model falls within the confidence intervals of the previous report from the NSW prisons, which associated HCV seroconversion with frequent injecting and needle and syringe sharing and the lack of effective prevention strategies in this setting [20]. This re-affirms the need for stronger HCV treatment and prevention programmes.

This study argues for further scale-up of DAA treatments in the prison. Model projections under the 2018 scenario indicate an annual total of 16 676 individuals incarcerated, including 5400 with chronic HCV. Hence, the current 1000 DAA treatments represent fewer than 20% of prisoners with chronic infection, and even the optimistic doubling of those treatment numbers to 2000 would still represent fewer than half of those who could theoretically be treated. Hence, even in the optimistic scenario there is only a modest treatment-as-prevention (TasP) effect evident. Furthermore, as the prisoner population continues to expand, continued scale-up of DAA treatment is required to match the growth in total prisoner population and to gain a greater TasP effect. This is consistent with previous models of DAA treatment scale-up in the general community, in which HCV treatments of four to eight of 100 PWID per year combined with harm reduction were required to achieve a $>$ 80% reduction in HCV incidence rate by 2030 [25].

The notion of 'improved OST' modelled here relates to the fact that existing data from the Australian prisons have not demonstrated a reduction in HCV incidence rate associated with provision of OST [4], despite clear evidence of its protective effect in the community [11]. The lack of such benefit in the prison setting may relate to periods when OST is typically unavailable, such as immediately upon imprisonment, insufficient dosing to confer a reduction in injecting frequency and the dynamic nature of IDU and

drug of choice in the prisons [4,8]. Many challenges remain in improving access, participation, adherence and retention of prisoners on OST [26]. Nevertheless, the model indicates that OST is key to reducing transmissions in the high HCV-prevalence prison setting.

The introduction of NSP was also projected to reduce the HCV incidence rate. It should be noted that the reduction in sharing behaviour due to NSP implemented in this model was largely derived from the positive outcomes of community NSP studies. Prison-based NSP is implemented only in very few countries and only in selected prisons [27]. Prison-based NSP is usually implemented via syringe distribution upon request from the prison doctor or counselling staff, exchange distribution of kits containing a new syringe or automatic distribution machines. Implemented programmes demonstrated one or more health benefits, but the strength of evidence was low [10]. In Australia, custodial officers have rejected NSP due to a previous HIV blood-filled syringe attack [10,28]. Nevertheless, this modelling study provides quantitative evidence that a combined approach can lead to HCV elimination.

The largely unrestricted delivery of DAA treatments in the community in Australia is expected to reduce chronic HCV prevalence in the prisons, as those newly incarcerated will have already been treated. In Australia, there is concern that DAA treatment efforts in the community, including in tertiary care, primary care and drug and alcohol services, may still have inadequate reach among the most marginalized populations, particularly those who become incarcerated [14]. This study suggests that good DAA coverage in the community, combined with a moderate increase of DAA treatments in the prisons and introduction of improved harm reduction via OST and/or NSP, makes HCV elimination feasible in the prisons [23].

It is important to note the limitations of the model. First, the estimated model parameters such as the proportion of PWID may not represent the actual rates in NSW prisons. These values were based on published literature, which utilized varied methods and may have not captured the whole NSW prison population. The transmission rate used here represents the overall population at the macroscopic level. This, however, may not capture the variation in the individual level due to the absence of information on individual IDU sharing networks. The actual transmission rate for an individual would be influenced by the person's average number of injecting partners per day. Similarly, the assumed effect of prevention strategies tested here were hypothetical, due to limited existing implementation in prison settings. Secondly, the model focused on IDU-related transmissions and disregarded other less likely modes of HCV transmission in the prison setting, such as tattooing and fights. Thirdly, the model assumed universal HCV screening, whereas the typical reality is that this is rare. As it estimated that 80% of all Australians with chronic HCV have been previously diagnosed, it may be argued that screening strategies are a lower priority [29]. Nevertheless, applying the actual rate of prison-based screening would further inform the implementation of HCV treatment and prevention strategies. Finally, while the model was able to recapitulate the existing trends in the prisoner population size, unpredictable variables in the future, notably legislative decisions, could greatly impact incarceration rates, sentence lengths and prisoner populations.

Correctional centres are designated as a priority setting for HCV prevention and treatment in Australia and globally [2,30–32]. The results of this study have clear potential to inform HCV elimination efforts in other prison systems in Australia, several of which feature generally similar populations, risk behaviours and HCV prevalence rates. Advocating for the scale-up of treatment and prevention programmes also applies to prison systems in other countries, given the inadequacy of OST and NSP implementation [33].

This model shows that there is considerable opportunity to reduce HCV incidence by engaging PWID in prison-based treatment and prevention programmes. More importantly, it shows the potential to eliminate HCV in prisons with combined efforts in treatment and prevention in both the prison setting and the general community. Future developments of the model could include an expansion to include a dynamic community-based component to further estimate the relative effect sizes of treatment in the prisons and community.

Declaration of interests

None.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1 Risk groups implemented in the model as referred to in the main manuscript.
Table S2 Sub-populations of individuals described in the community compartment.
Table S3 Initial population values utilized pertaining to the community-based subsets estimated from in 2005. Population values were estimated according to characteristics: IDU, HCV status and indigenous status.
Table S4 Parameters for assigning demographic characteristics, risk behaviors, HCV status, and liver disease stage of newly incarcerated individuals.
Table S5 Parameters* for in-prison events relating to transition between IDU risk groups.
Table S6 Parameters* for in-prison events relating to movement between prison locations.
Table S7 Parameters* for in-prison events relating to death.
Table S8 Parameters* for in-prison events relating to progression of HCV.
Table S9 Parameters* for in-prison events relating to progression of HCV.
Table S10 *P*-values comparing model output from 10, 50, 100, and 500 simulations in terms of the prisoner populations in minimum, medium, and maximum security prisons. Significance was based on a threshold of 0.05.
Table S11 Projected prisoner population as referred to in the main manuscript.
Table S12 Annual percentage change in prisoner population based on data from ABS and Corrective Services NSW.
Table S13 Calibration of prison sub-populations.
Table S14 Projected HCV incidence rate per 100 p.y. and HCV Ab prevalence as referred to in the main manuscript.
Table S15 Annual reduction in new incarcerations with HCV Ab+RNA+ status based on NSW estimates.
Table S16 Projected HCV incidence rate per 100 p.y. among incarcerated PWID under model scenarios as visualized in Figures 6-9, main manuscript.
Table S17 Annual new infections under DAA scenarios as visualized in Figures 6-9, main manuscript.
Table S18 Annual number of people with HCV Ab+ under DAA scenarios as visualized in Figures 6-9, main manuscript.
Table S19 Annual number of people with HCV RNA+ under DAA scenarios as visualized in Figures 6-9, main manuscript