

Can Difficult-to-Reuse Syringes Reduce the Spread of HIV Among Injection Drug Users?

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Sharing of syringes by injection drug users is a principal means by which the human immunodeficiency virus (HIV) is spread. Some have suggested that distributing syringes that are difficult to reuse (DTR) would slow the spread of HIV. We developed a simple mathematical model that describes how changes in the numbers of DTR syringes or regular syringes consumed over the course of a fixed number of injections affects the proportion of injections that are potentially infectious and, thus, the transmission of HIV. It suggests that increasing consumption of either type of syringe will reduce the proportion of potentially infectious injections, but that, per syringe added, the reduction is always greater if a regular rather than a DTR syringe is added. Similarly, introducing a certain number of DTR syringes and simultaneously reducing the consumption of regular syringes by the same number will increase, not decrease, the proportion of infectious injections. DTR syringes are more expensive than regular syringes, so there is little justification for substituting them for regular syringes.

The spread of the human immunodeficiency virus (HIV) and acquired immunodeficiency syndrome (AIDS) is among the most troubling problems facing

contemporary society. Sharing of used syringes by injection drug users (IDUs) is now the major form of HIV transmission in the US [Holmberg 1996]. One suggestion for controlling HIV has been to develop and disseminate syringes that cannot be reused by IDUs [Samuels, Koop, and Hartsock 1991].

It may not be feasible to develop a syringe that literally can never be reused, but difficult-to-reuse (DTR) syringes are being developed. The Office of Technology Assessment [1992] describes four design approaches: syringes containing a hydrophilic gel that disables the plunger or closes the passageway through the syringe after use; plungers that are disabled when the user attempts to reload the syringe; needles that are disabled after the first use of the syringe; and valves that prevent a second loading of the syringe.

Reducing the frequency with which a given syringe is reused or shared would reduce the transmission of HIV by that particular syringe, so DTR syringes have intrinsic appeal. However, if the total number of syringes and the frequency of injection remain constant, when some syringes are used less frequently, others must be used more frequently. Some syringes would become "safer," while others would become more dangerous. Which effect would be greater? The answer to that question determines whether substituting DTR syringes for regular syringes is beneficial.

Model for One Type of Syringe

To assess the impact DTR syringes might have on HIV transmission, we need to model how often an IDU injects with an infectious syringe. Kaplan [1989] realized

that such problems can be addressed by considering the syringe's perspective. Kaplan's model used differential equations to track not only IDUs as they move from an uninfected to an infected state, but also syringes as they move from an uninfected to an infectious state and back.

Our approach differs from Kaplan's previous work in four respects. First, we do not model changes in the proportion or number of IDUs who are infected. We focus entirely on the proportion of injections that are made with infectious syringes (referred to as *infectious injections*).

Second, Kaplan considered only one type of syringe. Syringes do not interact with each other, so if we assume syringes are selected randomly (as did Kaplan), multiple types of syringes can be modeled with multiple "copies" of a model for one syringe, differing only in the parameters describing the syringe.

Third, we do not follow individual syringes per se, but rather sequences of syringes that are used in succession. Over time, syringes become dull, break, or become clogged, and then are replaced with new, presumably sterile, syringes. Rather than explicitly model this aging process, we treat each syringe as infinitely lived but recognize that one way syringes can be "cleaned" is by being replaced. As long as the total number of syringes in circulation is not steadily and substantially increasing or decreasing and injection frequency does not depend on syringe age, this is merely a matter of notation and has no effect on the results.

Finally, we employ a discrete-time Markov model to find the probability that a syringe is infectious, where the epochs are

DIFFICULT-TO-REUSE SYRINGES

the instants of time just before a session in which a syringe is used to inject drugs. At each such epoch, a syringe can be in one of two states. It is either infectious or uninfected, denoted by the subscripts I and U, respectively. We therefore need to model the probabilities that from epoch to epoch an uninfected syringe becomes infectious (p_{UI}) and that an infectious syringe ceases to be so (p_{IU}).

For an uninfected syringe to become infectious by the next epoch, it must be (1) used by an infected user, (2) become infectious through that use, and (3) remain infectious until just before the subsequent use. The probabilities of these events are denoted by f , φ , and $1 - \omega$, respectively, where ω is the probability that a syringe which is infectious immediately after use ceases to be infectious before its next use. Then,

$$p_{UI} = f\varphi(1 - \omega). \quad (1)$$

For an infectious syringe to become uninfected by the next epoch, it must (1) be both used by an uninfected user (probability $1 - f$) and have that use render the syringe uninfected (probability θ) or (2) cease to be infectious between uses (probability ω). Note that from a syringe's perspective it makes no difference whether an uninfected user sterilizes the syringe before injection (e.g., with bleach) or "flushes" the syringe by injecting. With these definitions,

$$p_{IU} = (1 - f)\theta + (1 - (1 - f)\theta)\omega. \quad (2)$$

Syringes cease to be infectious between use sessions because they "dry out," killing the virus, or because the syringe is replaced. Let β be the probability of the for-

mer event, and suppose that the number of times a syringe is used is described by a geometric random variable with mean n . Then the probability it is replaced between any two uses is $1/n$, so the probability an infectious syringe ceases to be infectious between uses is $\omega = \beta + (1 - \beta)/n$.

The street life of a syringe is short—on the order of days or weeks [Kaplan and Heimer 1994; Hopkins 1988]. Relative to this, other parameters in the model change quite slowly. Hence, one would expect the fractions of syringes that are infectious or uninfected to be close to their steady-state values (denoted by P_I and P_U , respectively). In steady state, the rate at which uninfected syringes become infectious ($P_U * p_{UI}$) equals the rate at which infectious syringes become uninfected ($P_I * p_{IU}$), that is,

$$f\varphi(1 - \omega)P_U = (\omega + (1 - \omega)\theta(1 - f))P_I. \quad (3)$$

All syringes are either infectious or uninfected ($P_I + P_U = 1$). So Equation (3), together with the expression for ω , implies that

$$P_I = \frac{f\varphi}{f\varphi + \theta(1 - f) + \frac{\beta}{(1 - \beta)} + \frac{1}{(n - 1)(1 - \beta)}}. \quad (4)$$

The fraction of injections that are made with infectious syringes would be less than P_I to the extent that IDUs clean syringes during an injection session but before use, for example, by bleaching the syringe. Nevertheless, P_I is the quantity of interest here because promoting bleaching and distributing DTR syringes can be considered independent interventions and because P_I

represents the fraction of injections that have the potential to infect.

P_1 is decreasing in the likelihood of a syringe "drying out" (β); decreasing and convex in the likelihood of a syringe being rendered uninfected by an uninfected user (θ); and increasing and concave in the fraction of IDUs who are infected (f), the mean number of times a syringe is used (n), and the likelihood that an infected user renders a syringe infectious (ϕ). Thus, although the magnitude of P_1 depends on the specific parameter values, its basic shape is quite simple, does not depend on the parameter values, and is in accord with what would be predicted from knowing the dynamics of needle use.

Model for Multiple Types of Syringes

Suppose there is more than one type of syringe. The overall fraction of potentially infectious injections is the weighted sum of the fractions for each type of syringe, with weights equal to the proportion of all injections made with that type of syringe. We will denote that overall average by Z since it is a quantity one would like to minimize.

As long as IDUs select syringes at random, P_1 for each type of syringe can be computed from Equation (4) with n set equal to the average number of times a syringe of that type is used before being discarded. Here we focus on the special case of two types of syringes. In particular, we want to understand how the proportion of infectious injections would change if DTR syringes were introduced into the current environment in which all syringes are regular syringes. The outcome depends crucially on how the number of both DTR and regular syringes consumed after the

DTR syringes are introduced compares to the number of regular syringes consumed before DTR syringes are introduced. To stress this point, we measure numbers of syringes as multiples of the number of regular syringes being consumed before DTR syringes are introduced. In particular, let

$$s = \frac{\text{rate of consumption of syringes introduced by intervention}}{\text{rate of consumption of regular syringes before the intervention}}$$

and

$$r = \frac{\text{change in rate of consumption of regular syringes caused by intervention}}{\text{rate of consumption of regular syringes before the intervention}}.$$

For example, suppose a population of IDUs originally used 100,000 regular syringes per year, a program was established that distributed 60,000 DTR syringes per year, and as a result the use of regular syringes from nonprogram sources fell from 100,000 to 80,000 per year. This would be described by setting $s = 0.6$ and $r = -0.2$. Note that this scenario is not like a needle exchange that distributes three DTR syringes for each regular syringe returned and, in the process, distributes 60,000 DTR syringes a year. In a needle exchange, IDUs return used, not new, syringes, whereas the parameter r represents a change in consumption of (new) regular syringes. Indeed, if the syringes returned to a needle exchange were so old that they would never have been used again even if they had not been returned, then from the perspective of syringe use the exchange is indistinguishable from a pure syringe dis-

DIFFICULT-TO-REUSE SYRINGES

tribution. Such an exchange would be modeled by setting $r = 0$.

The parameter r is needed to allow for the possibility that the number of regular syringes obtained from nonprogram sources might change because of a DTR syringe program's existence. Examples of nonprogram sources include IDUs obtaining syringes through theft (for example, from hospitals), as gifts (for example, from relatives who are diabetic and receive syringes by prescription), from the black market, or by buying them in pharmacies (in states that have no drug paraphernalia statutes). For brevity, we refer to all these other sources collectively as *syringe diversion*. Policy makers do not directly control the rate at which IDUs consume regular syringes, but a DTR intervention might influence that rate.

To illustrate, consider a proposal to require hospitals to use DTR instead of regular syringes; if the rate of syringe theft from hospitals did not change, such a requirement might reduce diversion of regular syringes by one syringe for each DTR syringe that becomes available to IDUs. Syringe exchange and distribution programs could also affect diversion. For example, suppose IDUs seek a new syringe whenever their current syringe becomes dull and never for any other reason. If new regular syringes were given away, IDUs might respond by reducing diversion of syringes by a comparable amount, resulting in no effect on the rate of HIV infection. Alternatively, the very existence of syringe distribution might convince IDUs that the risk of HIV must indeed be great, leading them to increase the rate at which they obtain new diverted syringes.

The abstract model presented here can say little about any such behavioral response. However, it can describe conditions that a syringe exchange, syringe distribution, or other intervention must meet to reduce the number of injections that are potentially infectious. To do so, let n_D = average number of times a DTR syringe is used, and n_R = average number of times a regular syringe was used before DTR syringes were introduced.

We need to find n'_R , the average number of times regular syringes are used after DTR syringes are introduced.

There is no reason to believe syringe interventions would greatly affect the overall rate of injecting. Syringes are already available—even in jurisdictions that restrict their sale. Furthermore, they are available at a cost that is very small compared to the cost of the drugs they are used to inject [Caulkins 1992; Kaplan 1992]. Also, empirical data from syringe-exchange programs show no evidence of associated changes in the amount of drug use [Lurie et al. 1993; Normand, Vlahov, and Moses 1995]. If the number of injections remains the same after the introduction of DTR syringes, $n_R = (1 + r)n'_R + sn_D$, so

$$n'_R = (n_R - sn_D)/(1 + r). \quad (5)$$

(Equation (5) applies as long as $(1 + r + s)n_D \leq n_R$ and, thus, $n_D \leq n'_R$; if this condition were not satisfied, presumably DTR syringes would be used less often, on average, than n_D times.)

Since the fraction of injections made with DTR syringes is $(sn_D)/n_R$, the fraction of all injections that are potentially

infectious is

$$Z = \frac{s n_D}{n_R} P_I(n_D) + \frac{n_R - s n_D}{n_R} P_I(n'_R). \quad (6)$$

General Properties of the Model

Interesting and rather strong inferences can be derived from Equation (6) using elementary calculus and convexity arguments. All other things being equal, introducing DTR syringes reduces the fraction of infectious injections because Z is decreasing in s . However, Z is also decreasing in r , the change in the number of regular syringes. In other words, having more of either kind of syringe reduces the fraction of infectious injections.

By the convexity of $n P_I(n)$, when $r = -s$ (that is, the same number of syringes are consumed, but now some are DTR syringes), the proportion of infectious injections increases, regardless of the values of the other parameters. Likewise, if one has the choice of adding a certain number of DTR syringes or the same number of regular syringes (without reducing the original supply of regular syringes in either case), adding regular syringes does more to reduce the spread of HIV. Indeed, for any plan that involves DTR syringes, the proportion of infectious injections is always reduced if the number of DTR syringes consumed is reduced by some amount and the number of regular syringes consumed is increased by that same amount.

Of course, for any given reduction in the number of regular syringes consumed ($r < 0$), there is always a number of DTR syringes ($s > |r|$) that can be added such that the proportion of infectious injections is reduced. The remaining question is, how many DTR syringes must one add to

offset a reduction in the number of regular syringes? There are no simple analytical expressions describing these conditions, so we explore these numerically using estimated parameter values.

Estimating Parameter Values

We estimate the model's parameters in two ways. The first is to estimate each parameter individually. The second is to translate the model into terms consistent with the circulation-theory model for which parameter values have already been measured empirically [Kaplan 1994, 1995]. In both cases, we strive only to obtain reasonable estimates for the sake of illustration, not to imply a high degree of precision.

Direct Estimates

Holmberg [1996] estimates that the average prevalence of HIV among IDUs in 96 large US metropolitan areas is 14 percent, so we set $f = 0.14$. Kaplan [1989] assumes the probability that an injection by an uninfected user "flushes" an infectious syringe, thereby rendering it no longer infectious, is 0.25; we set $\theta = 0.33$ to reflect both flushing and bleaching. Kaplan [1989] assumes that the probability that a syringe becomes infectious when it is used by an infected user is $\varphi = 1.0$; we do as well.

Heimer et al. [1996] infected syringes with blood from AIDS patients and then attempted to culture HIV at regular time intervals. In most syringes, the virus survived for three weeks, suggesting that the probability the virus dies during the limited period between injections is very low. Hence, we take $\beta = 0.05$.

Gleghorn (personal communication) provided data from seven cities on the number of times IDUs report injecting

with their last syringe. The mean is 5.22. However, we are interested in the average number of times a syringe is used before it is discarded, which is different. If all the respondents injected at the same rate, then a random incidence calculation using these data suggests that the average syringe is used about 2.5 times before it is discarded.

Inserting these parameter values into Equation (6) yields Parameterization 1:

$$Z = \left(\frac{s n_D}{2.5}\right) \frac{0.14}{0.14 + 0.33643 + \frac{1.05263}{n_D - 1}} + \left(\frac{2.5 - s n_D}{2.5}\right) \cdot \frac{0.14}{0.14 + 0.33643 + \frac{1.05263(1 + r)}{1.5 - r - s n_D}}$$

Estimates Based on Circulation Theory Models

Multiplying the numerator and denominator of Equation (4) by $(1 - \beta)$, $(n - 1)/n$, and a parameter α representing the rate at which a syringe is used (for example, number of times per week) and evaluating at $n = n_R$ gives an expression that can be interpreted in terms of syringe circulation-theory models [Kaplan 1994, 1995]:

$$P_1(n_R) = \frac{\alpha(1 - \beta)f\varphi \frac{n_R - 1}{n_R}}{\alpha(1 - \beta)f\varphi \frac{n_R - 1}{n_R} + \alpha[(1 - \beta)\theta(1 - \beta) + \beta] \frac{n_R - 1}{n_R} + \frac{\alpha}{n_R}} = \frac{\lambda}{\lambda + \mu + \rho}$$

where

λ = rate at which uninfected syringes become infected per uninfected syringe per unit time,

μ = rate at which infected syringes become uninfected (other than by being replaced) per infected syringe per unit time, and ρ = rate at which syringes are removed and replaced per syringe per unit time.

From the syringe tracking and testing data associated with the New Haven syringe exchange, Kaplan [1994, 1995] estimates that $\lambda = 0.3675$ and $\mu = 0.1665$. Also, the mean circulation time for syringes prior to the start of the syringe exchange was estimated to be 23.5 days, suggesting that $\rho = 1/23.5 = 0.0426$.

These values of λ and ρ imply that $\lambda/\rho = f\varphi(1 - \beta)(n_R - 1) = 0.3675/0.0426 = 8.627$. Kaplan and Heimer [1992] estimated that $f = 0.6$ for this population, implying that $n_R > (8.627/0.6 + 1) = 15.38$. Since φ is near unity and β is small, we take $n_R = 16$.

Since

$$P_1(n) = \frac{\lambda}{\lambda + \mu + \rho \frac{n_R - 1}{n - 1}}$$

inserting these parameter values into Equation (6) gives Parameterization 2:

$$Z = \left(\frac{s n_D}{16}\right) \frac{0.3675}{0.3675 + 0.1665 + \frac{0.639}{n_D - 1}} + \left(\frac{16 - s n_D}{16}\right) \cdot \frac{0.3675}{0.3675 + 0.1665 + \frac{0.639(1 + r)}{15 - r - s n_D}}$$

Numerical Estimates of the Impact of DTR Syringes on the Spread of HIV

We would like to know what reduction in the number of regular syringes used would just offset the introduction of a

given number of DTR syringes, thereby leaving the proportion of injections that are potentially infectious unchanged. If the actual reduction in regular syringes diversion is more substantial than this break-even threshold change, introducing DTR syringes would increase the spread of HIV; if the actual reduction is less dramatic, introducing DTR syringes would reduce the spread of HIV.

Figure 1 shows, for each parameterization, combinations of numbers of DTR syringes introduced (s) and changes in the number of regular syringes used (r) such that the fraction of injections which are potentially infectious (Z) remains constant. Separate curves are shown for true "single

use" syringes ($n_D = 1$) and DTR syringes that are reused an average of two times ($n_D = 2$). When $n_D = 2$, the curves for Parameterizations #1 and #2 are virtually indistinguishable.

Figure 1 shows that (1) the results for Parameterizations 1 and 2 never differ by more than about 20 percent, even though some of the underlying parameter values (for example, n_R) are quite different; (2) the curves are nearly straight lines, so it makes sense to talk about a critical ratio of DTR syringes added relative to the reduction in regular syringes used; and (3) the critical ratio decreases as n_D increases and so is greatest for $n_D = 1$. It appears that as long as about 1.4 DTR syringes are intro-

Figure 1: If the change in the number of DTR syringes is a little larger, in absolute value, than the change in the number of regular syringes, there will be no change in the proportion of injections that are potentially infectious.

DIFFICULT-TO-REUSE SYRINGES

duced per unit reduction in consumption of regular syringes, the proportion of potentially infectious injections will not increase. Equivalently, as long as introducing 100 DTR syringes does not reduce diversion of regular syringes by more than about $100/1.4 = 70$ syringes, introducing DTR syringes will not increase the spread of HIV.

Figure 1 describes the conditions necessary for introducing DTR syringes to “do no harm.” Figure 2 describes the potential benefits of increasing the number of syringes. For each parameterization, Figure 2 considers (a) introducing a given number of DTR syringes with $n_D = 1$ without reducing the number of regular syringes used (that is, $r = 0$) and (b) increasing the

number of regular syringes used by a like amount.

As must be the case, for any given number of syringes added, the proportion of injections that are potentially infectious is reduced more if those syringes are regular syringes than if they are DTR syringes. However, for both parameterizations the differences are modest. If the DTR syringes are not true single-use syringes (that is, $n_D > 1$), the DTR syringes are more like regular syringes so the differences become even smaller.

Conclusions

The model we developed shows that when difficult-to-reuse (DTR) syringes are introduced, the impact on the proportion of injections that are potentially infectious

Figure 2: Adding syringes reduces the proportion of injections that are potentially infectious slightly faster if the syringes are regular rather than DTR syringes.

depends crucially on the number of both DTR and regular syringes consumed by IDUs after introduction of DTR syringes, relative to the number of regular syringes consumed beforehand. As with any model, its abstractions generate caveats. In particular, the model assumes that changing the availability of syringes would not affect the number of injections. Also, the model includes only intentional injections, not accidental needle sticks.

Subject to these caveats, the model suggests the following conclusions:

- (1) Increasing the number of either DTR or regular syringes consumed, holding constant all other factors including the number of injections, will reduce the proportion of infectious injections.
- (2) Per syringe added, the reduction in the proportion of infectious injections is always greater if a regular rather than a DTR syringe is added, although for the parameter values investigated here the differences are not very great.
- (3) If introducing a certain number of DTR syringes leads to an equal reduction in the number of regular syringes consumed, the proportion of infectious injections will increase, not decrease. This scenario might pertain if for a particular source of diverted syringes (for example, friends or family who are diabetics) regular syringes were replaced by DTR syringes, and there was no change in the rate of diversion from other sources. Similarly, if a syringe exchange substituted DTR for regular syringes while holding all other parameters including diversion constant, that would increase the rate of HIV transmission.
- (4) If introducing a certain number of

DTR syringes leads to a reduction in the number of regular syringes consumed which is less than 70 percent as great (for example, adding 100 DTR syringes reduces regular syringe consumption by no more than 70 regular syringes), then the proportion of infectious injections is unlikely to increase.

In summary, if the goal is to reduce the proportion of infectious injections, this model suggests that regular syringes are essentially always superior to DTR syringes.

Furthermore, several policy and logistical points bear consideration. First, DTR syringes are more expensive than regular syringes. Second, focus groups of IDUs report that because some DTR syringes interfere with elements of the injection process, such as *booting* (the practice of injecting the drug in a series of small injections, rather than as a single bolus) and *jacking* (pulling back on the plunger to confirm entry into the vein), IDUs are likely to prefer regular syringes [OTA 1992]. Clearly DTR syringes cannot reduce the spread of HIV if IDUs refuse to use them, at least as long as regular syringes continue to be available from illicit sources. Finally, it is not clear how DTR syringes could be introduced in large numbers into the pool of syringes used by IDUs. Based on this analysis, therefore, we do not recommend the use of DTR syringes as a strategy for reducing HIV transmission among IDUs.

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DIFFICULT-TO-REUSE SYRINGES

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