A Little Planning Goes a Long Way: Multilevel Allocation of HIV Prevention Resources

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Background. *HIV prevention funds are often allocated by decision makers at multiple levels. High-level decision makers may allocate funds to regions, and regional decision makers then allocate those funds to specific programs. Often, funds are allocated proportionally (e.g., in proportion to HIV incidence) rather than efficiently (i.e., to maximize HIV infections averted). The authors investigate the impact of efficient and proportional allocation methods at 2 different decision levels.* ***Methods.*** *The authors developed an optimization model of resource allocation at 2 levels—an aggregate upper level and multiple local levels—and considered efficient allocation and allocation proportional to HIV incidence. Using data from 40 U.S. states, they compared 4 strategies for allocating HIV prevention funds.* ***Results.*** *The greatest health benefit (HIV infections averted) occurred when efficient allocations were made at both levels. When funds were allocated proportionally at the higher level and efficiently at the lower level, the health benefit was about 5% less than when efficient allocations were made at both levels. When funds were allocated efficiently at the higher level and proportionally at the lower level, the health benefit was 15% less than when efficient allocations were made at both levels. The least health benefit (23% less than when efficient allocations were made at both levels) occurred with proportional allocation at both levels.* ***Conclusions.*** *Efficient allocation only at the higher level cannot overcome poor allocations at lower levels. Moreover, efficient allocation at the lower level is likely to yield greater gains than efficient allocation at the higher level. Thus, upper-level decision makers, such as donor organizations, should develop incentives to promote efficient allocation by lower-level decision makers.*

Key words: *HIV; AIDS; HIV prevention; resource allocation; optimization.* ***(Med Decis Making 2007;27:71–81)***

In the United States, funds for HIV prevention are allocated by the Centers for Disease Control and Prevention to 65 different HIV Prevention Community Planning Groups (CPGs).[1] The CPGs typically comprise representatives from the local community and include members of communities that are at highest risk of acquiring HIV infection. Given an allocation of funds, each CPG decides which specific programs to fund and how much to invest in each.

A similar 2-level allocation problem is encountered in many international HIV funding situations in which resource allocation decisions are made at a national or international level before any funds are allocated to individual programs. For example, a country may apply for funds for HIV prevention from the Global Fund to Fight AIDS, Tuberculosis and Malaria. If the country is successful, funds are distributed from the World Bank to 1 or more local principal recipients who then distribute the funds to local subrecipients.[2]

A number of mathematical models have been developed to assist decision makers with HIV resource allocation decisions.[3–8] A typical model seeks to minimize the number of new infections that occur over some time period subject to constraints on total budget. In practice, HIV prevention resources are often allocated using simple decision rules such as allocation proportional to HIV prevalence, HIV incidence, or population size.[9,10] Zaric and Brandeau[5] showed how the number of HIV infections prevented varies depending on whether resources are allocated efficiently (to maximize HIV infections averted) or in

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proportion to HIV incidence, HIV prevalence, or population size. Kaplan and Merson[11] argued that equity considerations (e.g., funding in proportion to the number of AIDS cases reported) may be important when resources are allocated locally. They showed that some equity considerations can be met with only small reductions in efficiency but that allocating all resources on the basis of equity results in a large reduction in efficiency.

Much of the formal modeling of HIV resource allocation assumes a decision maker who is in control of the entire resource allocation process. However, as described above, this does not reflect the method by which resources are allocated in many situations. Lasry and others[12] examined this situation with a model in which a high-level decision maker allocates funds to 2 regions and regional decision makers then allocate those funds to 2 prevention programs that each target a different subpopulation.

In this article, we develop and analyze a more realistic model with multiple local regions and subpopulations. We address the following questions: If HIV prevention resources are allocated at 2 levels, what is the impact on the number of HIV infections averted of efficient versus proportional allocation at each level? Can the allocation be improved if the upper-level decision maker has knowledge of the lower-level decision makers' allocation methods? Using data for 40 U.S. states and for HIV prevention programs targeted to 3 risk groups, we compare 4 strategies for allocating HIV prevention funds.

METHODS

We developed a 2-level resource allocation model in which an upper-level decision maker allocates funds to a number of regions and then a separate decision maker in each region allocates those funds to specific programs (Figure 1). Let i be an index over regions, $i = 1, \ldots, n$, and let j be an index over risk groups, $j = 1, \ldots, m$. We assumed that 1 program is available for each risk group; thus, the index j is also used for programs.

The upper-level decision maker has total funds B to allocate and allocates an amount x_i to region i, $i = 1, \ldots, n$. The decision maker in region i then has an amount x_i to allocate and allocates an amount y_{ij} to program j (and corresponding risk group j), $j = 1, \ldots, m$. A nonzero lower limit on investment in a program may be imposed because of equity considerations. An upper limit on investment may be imposed because of equity considerations or perhaps an upper limit on the fraction of the targeted population that can be reached by an intervention.

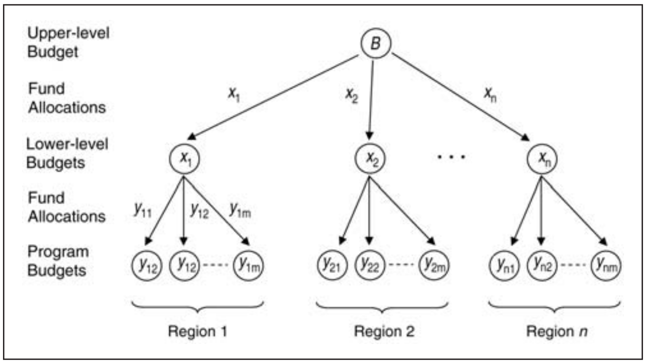

Figure 1 Schematic of the 2-level resource allocation problem. The upper-level decision maker has a budget B *and allocates an amount* x_i *to each region* i. *The lower-level decision maker in region* i *has a budget* x_i *and allocates an amount* y_{ij} *to each program* j *in region* i.

Similar to other HIV resource allocation models,[3,10,11] we assumed a fixed time horizon of length T and let h_{ij} be the estimated number of HIV infections prevented in region i over time T for each dollar invested in program j. The total number of HIV infections prevented in region i by the allocation of resources $(y_{i1}, y_{i2}, \ldots, y_{im})$ is $H_i = h_{i1}y_{i1} + h_{i2}y_{i2} + \ldots + h_{im}y_{im}$, and the total number of HIV infections prevented in all regions is $H_1 + H_2 + \ldots + H_n$. One method of estimating h_{ij}[10] is to estimate the cost per person of program j (c_j), the size of risk group j in region i (n_{ij}), the baseline number of new infections that will occur in risk group j in region i over time T (r_{ij}), and the reduction in the rate of infection (e_j) that can be achieved by the maximum possible investment in program j. Then, $h_{ij} = (r_{ij} \times e_j)/(c_j \times n_{ij})$.

As in Lasry and others,[12] we considered 4 methods by which resources can be allocated, corresponding to whether the resource allocation problem at each level is solved efficiently (to maximize HIV infections averted) or using a proportional allocation method (in proportion to HIV incidence). At the upper level, the proportional allocation method allocates funds to regions in proportion to HIV incidence in each region; at the lower level, this method allocates funds to each program in proportion to HIV incidence in the corresponding risk group. We assumed that limits on investment are taken into account by the efficient allocation method but not by the proportional allocation method. We denote the 4 possible approaches as efficient-efficient (EE), efficient-proportional (EP), proportional-efficient (PE), and proportional-proportional (PP). The appendix provides details of the mathematical formulation and solution of these problems.

We allowed for the possibility that some fraction r ($0 \le r \le 1$) of the total prevention funds are reserved for proportional allocation. When $r = 1$, all funds are reserved for proportional allocation and all allocation strategies reduce to strategy PP.

To evaluate the allocation strategies, we obtained data for 38 U.S. states plus Puerto Rico and Washington, DC (n = 40) and 3 risk groups (m = 3): injection drug users (IDUs), men who have sex with men (MSM), and heterosexuals. We obtained estimates of the population of each region.[11] For each risk group in each region, we obtained estimates of the group size, HIV prevalence, and HIV incidence.[11] We considered a 1-year time horizon and assumed that the total annual budget for HIV prevention was $412 million.[11]

We used data on the potential cost and effectiveness of interventions in each population as reported elsewhere[10]; these data, shown in Table 1, included a base case as well as optimistic and pessimistic cases. We assumed that each intervention could reach only a fraction of the targeted population (Table 1). This provides an upper limit on risk reduction and, when efficient allocation is used, provides an upper limit on investment. Consider, for example, the intervention targeted to IDUs: In the base case, this intervention costs $300 per person and reduces risk by 20% among individuals it reaches but can reach only 50% of individuals in the target population. If this intervention is implemented in a target population of 5000 IDUs, only 2500 individuals can be reached (5000 × 0.5); thus, the corresponding maximum (average) reduction in risk that can be achieved in this population is 0.05 (0.10 × 0.50). If efficient allocation is used, no more than $750 000 (2500 × $300) will be spent on this population.

The upper and lower bounds on the amounts invested were determined as functions of other parameters in the model. The lower bound on the amount invested in each region or program was determined by the value of r. When efficient allocation was used, the upper bound on the amount invested in any region or program was determined by the proportion of each group that can be reached (Table 1). When proportional allocation was used, we assumed that there was no upper bound on the amount invested. We did not consider the possibility of higher lower bounds or lower upper bounds, although both can be accommodated by our models.

Table 1 Estimates of Intervention Effectiveness

Intervention Targeted to	Pessimistic Scenario	Base Case Scenario	Optimistic Scenario
Injection drug users			
Cost per person reached ($)	700	300	100
Risk reduction per person reached	0.10	0.20	0.40
Fraction who can be reached	0.25	0.50	0.75
Men who have sex with men			
Cost per person reached ($)	500	250	50
Risk reduction per person reached	0.25	0.40	0.55
Fraction who can be reached	0.25	0.50	0.75
Heterosexuals			
Cost per person reached ($)	500	300	140
Risk reduction per person reached	0.10	0.15	0.25
Fraction who can be reached	0.25	0.50	0.75

Source: Data from Ruiz and others.[10]

The model was implemented in an Excel spreadsheet. We validated the model by comparing results from strategy EE to those found elsewhere.[10,11]

RESULTS

For each allocation method, Table 2 shows the total amount of funding received by each region and the total number of HIV infections averted for the case $r = 0$ (no funds reserved for proportional allocation) and $r = 50\%$ (half of all funds reserved for proportional allocation). For both values of r, the greatest health benefit (i.e., HIV infections averted) occurred when efficient allocations were made at both the upper and lower decision-making levels (strategy EE). The next highest health benefit was achieved by strategy PE: When funds at the higher level were allocated proportionally but funds at the lower level were allocated efficiently, the health benefit was only about 5% less than when funds were allocated efficiently at both levels. Strategy EP generated the 3rd highest health benefit (about 15% less than strategy EE), suggesting that if efficient allocation is used, more benefit is accrued by applying it at the lower level. The least health benefit (23% less than EE) accrued from

Table 2 Funding by Region (x_i in \$1000) under Different Allocation Methods and Resulting Total HIV Infections Averted

	Allocation Method							
	No Funds Reserved for Proportional Allocation				50% of Funds Reserved for Proportional Allocation			
Region	**EE**	**EP**	**PE**	**PP**	**EE**	**EP**	**PE**	**PP**
Alabama	613	0	725	725	867	363	725	725
Arizona	3813	8052	3064	3064	4619	8052	3064	3064
Arkansas	625	1349	1029	1029	901	1349	1029	1029
California	40 288	79 093	45 084	45 084	51 347	79 093	45 084	45 084
Colorado	2350	4648	2891	2891	3065	4648	2891	2891
Connecticut	6703	5642	10 654	10 654	7693	5642	10 654	10 654
Delaware	1348	1027	1256	1256	1418	1027	1256	1256
Washington, DC	11 490	7946	20 095	20 095	14 379	10 047	20 095	20 095
Florida	46 635	45 506	34 625	34 625	37 268	38 337	34 625	34 625
Georgia	7388	6084	7503	7503	8400	6084	7503	7503
Hawaii	1925	3001	1148	1148	2131	3001	1148	1148
Illinois	17 965	30 794	22 347	22 347	19 340	25 466	22 347	22 347
Indiana	2075	0	2339	2339	2849	1169	2339	2339
Kansas	500	778	303	303	554	778	303	303
Kentucky	1125	2464	996	996	1396	2464	996	996
Louisiana	5080	4947	3692	3692	5518	4947	3692	3692
Maryland	9438	6797	16 251	16 251	11 345	8126	16 251	16 251
Massachusetts	13 550	10 689	9604	9604	14 459	10 689	9604	9604
Michigan	11 708	11 463	7027	7027	12 303	11 463	7027	7027
Minnesota	2500	3879	1462	1462	2760	3879	1462	1462
Missouri	5000	10 584	4515	4515	6191	10 584	4515	4515
Nebraska	938	1339	541	541	1019	1339	541	541
Nevada	1825	4983	1862	1862	2415	931	1862	1862
New Jersey	32 370	20 704	31 452	31 452	32 370	20 704	31 452	31 452
New Mexico	775	1329	520	520	883	1329	520	520
New York	76 980	53 962	94 801	94 801	70 268	53 962	94 801	94 801
North Carolina	3325	7869	3075	3075	4213	7869	3075	3075
Ohio	9738	16 239	6247	6247	10 988	16 239	6247	6247
Oklahoma	2300	3750	2100	2100	2706	3750	2100	2100
Oregon	1938	0	2046	2046	2603	1023	2046	2046
Pennsylvania	21 665	17 089	24 177	24 177	23 462	17 089	24 177	24 177
Puerto Rico	11 513	9644	14 627	14 627	7993	9644	14 627	14 627
Rhode Island	1848	1667	1537	1537	2037	1667	1537	1537
South Carolina	2123	3074	1429	1429	1708	3074	1429	1429
Tennessee	3350	7273	2750	2750	4092	7273	2750	2750
Texas	37 075	0	18 590	18 590	21 840	9295	18 590	18 590
Utah	1238	2503	985	985	1487	2503	985	985
Virginia	2088	0	2534	2534	2959	1267	2534	2534
Total infections averted	3896	3330	3748	3002	3808	3320	3606	3002

Note: EE = efficient allocation at both upper and lower decision-making levels; EP = efficient allocation at the upper decision-making level and proportional allocation at the lower level; PE = proportional allocation at the upper level and efficient allocation at the lower level; PP = proportional allocation at upper and lower decision-making levels. Strategies PE and PP generated the same allocation of funds to regions (see table entries) but different allocations of funds to risk groups (not shown in the table); this difference in allocations is reflected in the total number of HIV infections averted by the 2 strategies (last row of table).

strategy PP. Note that the strategies PE and PP generated the same allocation of funds to regions (values shown in Table 2) but different allocations of funds to risk groups (not shown in Table 2). By allocating funds efficiently at the local level rather than proportionally, strategy PE led to a significantly higher health benefit than strategy PP. The ordering of the 4 strategies was the same in the optimistic and pessimistic scenarios.

Table 3 shows the amount allocated to each risk group under each strategy and the resulting total number of HIV infections averted in that risk group.

Table 3 Total Funding ($1000) and HIV Infections Averted by Risk Group

	Allocation Method							
	No Funds Reserved for Proportional Allocation				50% of Funds Reserved for Proportional Allocation			
	EE	EP	PE	PP	EE	EP	PE	PP
Total funding ($1000)								
IDU	135 030	178 139	117 880	206 222	133 858	179 091	129 845	206 222
MSM	214 838	138 407	197 600	106 061	214 838	138 269	173 940	106 061
HET	62 132	95 454	96 520	99 717	63 304	94 640	108 215	99 717
Total	412 000	412 000	412 000	412 000	412 000	412 000	412 000	412 000
HIV infections averted								
IDU	1648	1717	1564	1648	1618	1735	1595	1648
MSM	1959	1335	1836	1029	1959	1319	1648	1029
HET	289	278	348	325	231	266	363	325
Total	3896	3330	3748	3002	3808	3320	3606	3002

Note: EE = efficient allocation at both upper and lower decision-making levels; EP = efficient allocation at the upper decision-making level and proportional allocation at the lower level; PE = proportional allocation at the upper level and efficient allocation at the lower level; PP = proportional allocation at the upper and lower decision-making levels; IDU = injection drug users; MSM = men who have sex with men; HET = heterosexuals.

When proportional allocation was used at either or both decision-making levels, more funding was allocated to heterosexuals compared to the efficient allocation. Although, in most cases, more HIV infections were averted among heterosexuals as a result of the increased funding, the increase was not enough to offset the decrease in HIV infections averted among IDUs and MSM.

When $r = 0$, strategies involving efficient allocation may have undesirable consequences. For example, under strategy EE, of the $40.3 million allocated to California, all would be spent on MSM and none would be allocated to IDUs or heterosexuals. Under strategy EP, 5 states—including Texas, which has the 5th largest number of HIV cases—would receive no funds.

Reserving half of all funds for proportional allocation (rightmost 4 columns of Table 2) decreased the total health benefit by only a small amount (0%–4%) compared to the same allocation method with no funds reserved for proportional allocation. Figure 2 shows the total number of infections averted as a function of the percentage of funds reserved for proportional allocation (r ranging from 0 to 1). The top line in Figure 2 replicates results in Kaplan and Merson.[11] The number of HIV infections averted was significantly diminished only for r greater than 50%. The effect of the earmarking was most pronounced for the EE method: For $r = 50\%$, the health benefit was diminished by only about 4% compared to the case of no earmarking; for $r = 80\%$, the health benefit was diminished by 10%; and for $r = 100\%$, the benefit was diminished by approximately 25%. The effect of earmarking was less pronounced for the other allocation methods.

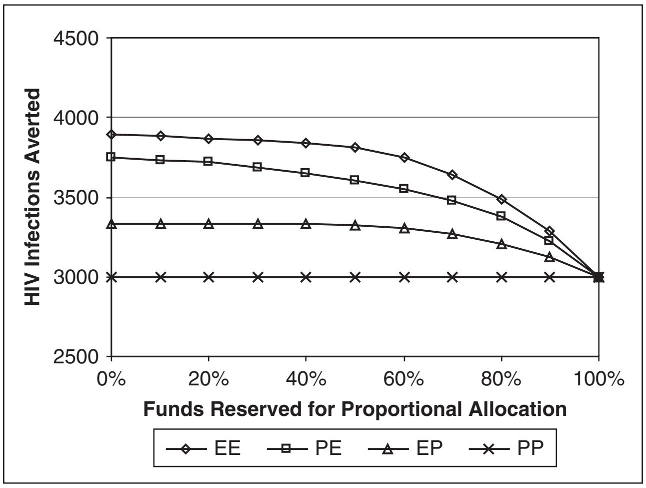

Figure 2 Infections averted under each allocation method as a function of the fraction of total funds reserved for proportional allocation. The top line reproduces results found elsewhere.[11] EE = efficient allocation at both upper and lower decision-making levels; EP = efficient allocation at the upper decision-making level and proportional allocation at the lower level; PE = proportional allocation at the upper level and efficient allocation at the lower level; PP = proportional allocation at the upper and lower decision-making levels.

Under our base case assumptions, a maximum of 4555 infections could be averted nationally (assuming a maximum possible investment in each prevention program in each region). We calculated the budget required to prevent this number of infections under various strategies. When $r = 0$, a budget of \$743 million would be sufficient to prevent this many infections with the EE strategy. Preventing a similar number of infections would cost \$1.67 billion using PE, \$1.58 billion using EP, and \$5.20 billion using PP. When $r =$ 50%, preventing 4555 infections would cost similar amounts. When r = 90%, preventing 4555 infections would cost \$1.21 billion using EE, \$2.53 billion using PE, \$2.24 billion using EP, and \$4.37 billion using EE.

If a lower-level decision maker is known to allocate HIV prevention funds efficiently, then the upper-level decision maker can use that information to adjust the allocation to that region accordingly. Table 4 shows the change in the amount of funding received by each region and the change in the total number of infections averted nationally if that region is known to allocate efficiently but all other regions use proportional allocation methods. In all cases, the switch by 1 region to efficient funding led to an increase in the total number of HIV infections averted.

However, the switch to efficient allocation in a given region did not always result in more funds being allocated to that region. In fact, for 21 of 40 regions, the switch to efficient allocation led to a decrease in funds received. For example, if California were to switch to efficient allocation while all other states used proportional allocation, the funding allocated to California would decrease by approximately \$38.8 million, but 69 more HIV infections would be averted nationally. Ninety additional infections would occur in California because of the decreased funding, but 159 fewer infections would occur elsewhere as a result of allocating the extra \$38.8 million available to other regions. This occurs because California is able to avert a relatively large number of infections per dollar invested in MSM, compared to investment in programs targeted to IDUs and heterosexuals. When California switches to efficient allocation, the upper-level decision maker is able to redistribute funds that would be directed to California IDUs and heterosexuals to higher risk groups in other regions.

Table 4 Impact on Funding to Individual Regions and Total HIV Infections Averted If Efficient Allocation Is Made in 1 Region at a Time while All Others Continue to Use Proportional Allocation

Region	Change in Region's Funding (\$1000)	Increase in Total Number of HIV Infections Averted
Alabama	613	1
Arizona	(4239)	6
Arkansas	(724)	1
California	(38 806)	69
Colorado	(2298)	3
Connecticut	1061	8
Delaware	320	1
Florida	1129	30
Georgia	1304	7
Hawaii	(1076)	3
Illinois	(12 829)	47
Indiana	2075	6
Kansas	(278)	0
Kentucky	(1339)	2
Louisiana	133	6
Maryland	2641	26
Massachusetts	2861	20
Michigan	244	12
Minnesota	(1379)	3
Missouri	(5584)	11
Nebraska	(402)	1
Nevada	(3158)	5
New Jersey	11 666	37
New Mexico	(554)	2
New York	2225	105
North Carolina	(4544)	8
Ohio	(6501)	17
Oklahoma	(1450)	2
Oregon	1938	5
Pennsylvania	4576	31
Puerto Rico	1869	6
Rhode Island	181	3
South Carolina	(952)	2
Tennessee	(3923)	7
Texas	15 100	31
Utah	(1265)	2
Virginia	2088	6
Washington, DC	3544	22
Washington	(5435)	8
Wisconsin	(1600)	3

If some regions lose funds and avert fewer infections as a result of switching from proportional to efficient allocation, they may have no incentive to switch to efficient allocation. The upper-level decision maker could address this by guaranteeing enough funds to a region so that the same number of infections could be averted when efficient allocation is used. For example, under strategy EP, California would receive \$79 million, which would be allocated to avert 515 infections. If California used efficient allocation, a budget of \$69 million would suffice to avert 515 infections. If California were known to allocate efficiently, the upper-level decision maker could allocate $69 million to California (where 515 infections would be averted) and distribute the remaining $10 million to other regions. Compared to EP, 40 more infections would be averted nationally.

Our baseline analyses assumed that the proportional allocation method would allocate funds in proportion to HIV incidence. Figure 3 shows the effect of other proportional allocation methods[5] (using strategy PP) for budget levels ranging from $0 to $800 million. With a budget of $300 million, the EE strategy yielded 3349 infections averted. For the same budget, allocation proportional to the number of HIV-infected individuals ("HIV+") averted 2803 infections (16% less than EE), allocation proportional to HIV incidence ("New Inf.") averted 2564 infections (23% less than EE), equal allocation to risk groups regardless of size ("33%") averted 2414 infections (28% less than EE), and allocation proportional to the size of the at-risk population ("At Risk") averted 1885 infections (44% less than EE).

The relative health benefit achieved for each type of proportional allocation depended on the total budget: For example, for a budget less than $550 million, allocation based on the number of at-risk individuals led to the smallest number of HIV infections averted, whereas for a larger budget, this method led to the greatest number of HIV infections averted. Allocation based on the number of at-risk individuals tends to allocate relatively more funds to states with low prevalence and incidence. For small budgets, this leads to poor performance, as funds are best used elsewhere. However, for large budgets, this is an advantage of the at-risk method. The other methods may cause too much money to be allocated to high-risk groups relative to the proportions of these groups that can be reached by HIV prevention programs. For a large enough budget, all proportional allocation methods will eventually reach the same upper limit on the number of infections averted. This upper limit is determined by the group sizes and the effectiveness of the interventions (see Table 1).

Figure 4 shows, for each definition of proportional allocation, the number of infections averted for each of the 4 allocation methods for budgets ranging from $0 to $1 billion. In all cases, the strategy of proportional allocation at both the upper and lower decision-making levels (strategy PP) always performed worse than the strategies that used proportional allocation at only 1 level (strategies EP and PE), which always performed worse than the efficient allocation method (strategy EE). However, the relative ordering of the allocation strategies EP and PE was not fixed. The figure caption indicates how proportional allocation was defined for each case: "At Risk" means that funds were allocated in proportion to risk group sizes; "HIV+" means that funds were allocated in proportion to the number of HIV-infected individuals; "New Inf." means that funds were allocated in proportion to the number of new HIV infections; "33%" means that funds were allocated to regions on the basis of HIV incidence, and then one-third of funds allocated to each region were allocated to each risk group. The base case budget was $412 million.

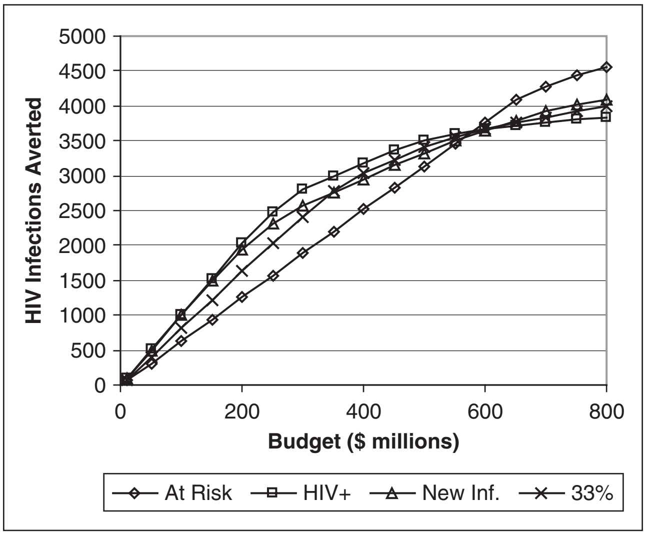

Figure 3 The impact of different proportional allocation rules on the number of HIV infections averted, using proportional allocation at both decision-making levels (strategy PP). "At Risk" means that funds were allocated in proportion to risk group sizes; "HIV+" means that funds were allocated in proportion to the number of HIV-infected individuals; "New Inf." means that funds were allocated in proportion to the number of new HIV infections; "33%" means that funds were allocated to regions on the basis of HIV incidence and then one-third of funds allocated to each region were allocated to each risk group. The base case budget was $412 million.

DISCUSSION

We analyzed the allocation of HIV prevention resources at 2 decision-making levels. The greatest health benefit was achieved when resources at both levels were allocated so as to maximize HIV infections averted (the EE strategy). The least health benefit was achieved when resources were allocated

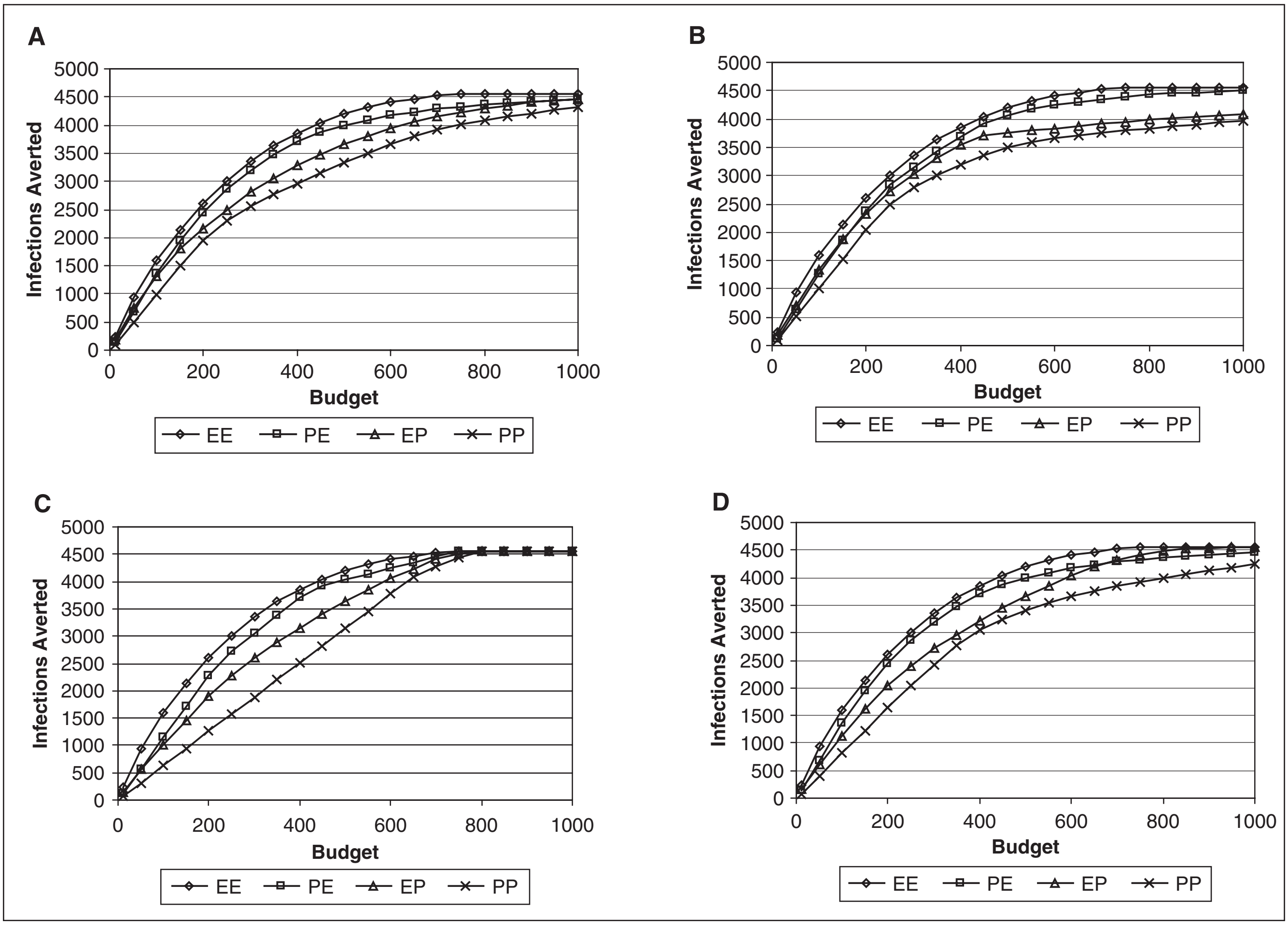

Figure 4 *Number of infections averted for different levels of budget and different definitions of proportional allocation. (A) New infections. (B) Prevalence. (C) Total at risk. (D) Thirty-three percent per risk group. EE = efficient allocation at both upper and lower decision-making levels; EP = efficient allocation at the upper decision-making level and proportional allocation at the lower level; PE = proportional allocation at the upper level and efficient allocation at the lower level; PP = proportional allocation at upper and lower decision-making levels.*

proportionally at both levels (the PP strategy). An intermediate level of health benefit was achieved by mixed strategies in which allocation was made efficiently at 1 decision-making level and proportionally at the other level (the EP and PE strategies). Even when up to 50% of funds were reserved for proportional allocation, efficient allocation of the remaining funds—at either level—generated significantly more health benefit than the strategy of purely proportional allocation.

For the mixed strategies, a larger health benefit was achieved by efficient allocation at the lower level (strategy PE) than by efficient allocation at the upper level (strategy EP). This suggests that an upper-level decision maker can use efficient allocation to overcome some limitations of proportional allocation at the lower level but that the use of efficient allocation at only the upper level cannot completely overcome the impact of proportional allocation at the lower level.

Many international aid organizations require detailed planning by aid recipients prior to funding. For example, countries applying for funds through the Global Fund to Fight AIDS, Tuberculosis and Malaria must submit a detailed plan to the Global Fund through a country coordinating mechanism. The plan is reviewed for technical merit before a funding decision is made.[2] Our finding that PE is usually better than EP and always better than PP suggests that this process makes sense. If funds are allocated efficiently at the local level, then a donor can allocate equitably across regions and achieve some of the gains that would have been possible if the donor had optimally allocated funds directly to programs.

When we considered the possibility of 1 region switching to efficient allocation while all others continued to use proportional allocation, we found that the switch always resulted in more total infections averted and was therefore beneficial overall. However, in many cases, the region that switched to efficient allocation received less funding from the upper-level decision maker. This suggests that upper-level decision makers may need to create incentives to convince lower-level decision makers to adopt efficient allocation methods, for example, a guarantee of funding sufficient to avert the same estimated number of infections that would be averted if the region used proportional allocation.

We considered 4 proportional allocation methods. Such proportional allocation methods may be a heuristic means of achieving equity among population groups and/or regions. Several other notions of equity exist and could be incorporated into this type of analysis.[13] Regardless of how equity is defined, tradeoffs between equity and efficiency are likely to occur, and the use of efficient allocation at either the upper or lower level can increase health benefits.

We assumed that the upper-level decision maker has complete knowledge of how allocation decisions will be made at the lower level. This may be realistic if the upper-level decision maker has received detailed plans from lower-level decision makers. However, if the upper-level decision maker has incomplete information about lower-level decisions, then it may be necessary to incorporate into the upper-level problem a probability distribution over possible lower-level decisions. In this case, the upper-level decision maker could assign a probability that each lower-level decision maker will allocate on the basis of different techniques. The upper-level decision maker could then account for these probabilities and their resulting outcomes when allocating to regions, using the goal of maximizing expected health benefit over different allocation methods that the lower-level decision makers might use.

HIV funding decisions are sometimes made at more than 2 levels. In Mozambique, for example, all funds for HIV/AIDS are coordinated by the National AIDS Council (NAC).[14] Funds from the federal government and foreign donors are directed to the NAC, which then distributes funds to provincial, regional, and local governments. Our model could be readily extended to more than 2 levels and used to estimate the efficiency losses that occur as part of the equity/efficiency tradeoff at multiple levels. Our model could also be readily extended to other diseases, such as tuberculosis and malaria, for which prevention resources are allocated at multiple levels.

Our analysis has several limitations. We did not consider HIV epidemic dynamics; thus, our analysis is limited to a time horizon short enough such that epidemic dynamics can be ignored. Over long time horizons, models that consider epidemic dynamics may lead to different allocations than models that do not.[15] Resource allocation models that incorporate epidemic dynamics have been solved for small numbers of populations and programs,[4,5] but such models may be intractable for larger problems such as the one we considered. We assumed that the benefits of interventions were linear in the amounts invested. This may not be true if, for example, individuals reached later by an intervention are less willing to change behavior than individuals reached by initial investment in the intervention. The relationship between risk reduction and the amount invested in a program has been shown to be important in HIV prevention resource allocation decisions.[5,6,16] Finally, we assumed a single decision maker (or decision-making entity) at each level. Our conclusions may not be valid if allocations are made by multiple decision makers (either at the upper level or in a given region) who have incomplete knowledge of each other's decisions.

Upper-level decision makers may be in a better position than lower-level decision makers to employ efficient allocation methods. However, our analysis suggests that efficient allocation often yields greater gains when applied at the lower level. When multiple regions compete for funds from a common budget, the possibility of reduced funding may serve as a disincentive for regions to invest in the effort required for efficient allocation. Thus, it is important for organizations that fund HIV prevention and treatment to develop incentives to encourage efficient allocation by recipients.

A switch from heuristic to efficient allocation methods will likely result in some regions or programs receiving lower levels of funding than they currently receive. Although efficient allocation always results in the greatest total number of infections averted, the gains for some regions or programs may come at the expense of reduced funding levels elsewhere. Those regions or programs receiving reduced funds would likely lobby to maintain their funding levels. Thus, a plan to use efficient allocation must be accompanied by efforts to educate all affected groups about the consequences of different allocations of resources.

Budgets for HIV prevention are limited. Indeed, the current annual shortfall in HIV prevention funding in the United States may exceed $1.85 billion.[17] In Sub-Saharan Africa, funding in 2003 was $2.9 billion short of estimated needs of $6.5 billion.[18] Methods for allocating HIV prevention resources that use efficient allocation at at least 1 level avert more infections than proportional allocation and should be part of a strategy of addressing current shortfalls in HIV prevention funding.

APPENDIX
Details of Allocation Methods

The lower-level decision maker i may allocate resources (x_i) using the proportional allocation method. We denote this solution by $y_{ij}^p(x_i)$ and denote the resulting number of infections averted by $H_i^p(x_i) = y_{i1}^p(x_i)h_{i1} + y_{i2}^p(x_i)h_{i2} + \ldots\ y_{im}^p(x_i)h_{im}$, $i = 1, \ldots, n$, where h_{ij} is the estimated number of HIV infections prevented in region i over time T for each dollar invested in program j.

Alternately, the lower-level decision maker may allocate resources to maximize the number of HIV infections averted as a result of the investment. The efficient lower-level allocation in region i, $y_{ij}^*(x_i)$, $i = 1, \ldots, n$, is the solution to

$$\max_{y_{i1},\ldots,y_{im}} y_{i1}h_{i1} + y_{i2}h_{i2} + \ldots + y_{im}h_{im}$$

$$\text{s.t.} \quad \sum_{j=1}^{m} y_{ij} \le x_i$$

$$L_{ij} \le y_{ij} \le U_{ij} \quad \text{for all } j$$

$$y_{ij} \ge 0 \quad \text{for all } j,$$

where L_{ij} and U_{ij} denote, respectively, lower and upper limits on the investment y_{ij}. We denote the resulting number of HIV infections averted by $H_i^*(x_i) = y_{i1}^*(x_i)h_{i1} + y_{i2}^*(x_i)h_{i2} + \ldots\ y_{im}^*(x_i)h_{im}$, $i = 1, \ldots, m$.

The upper-level decision maker may allocate resources using the proportional allocation method. We denote this solution by x_i^p. When the upper-level problem is solved using proportional allocation, then x_i^p is substituted into the budget constraint of the lower-level problem. When both problems are solved using proportional allocation (PP), no optimization problem is solved. Thus, when proportional allocation is used at the upper level, the number of HIV infections averted is either

$$\text{(PE)} \quad H_1^*(x_1^p) + H_2^*(x_2^p) + \ldots + H_n^*(x_n^p),$$

or

$$\text{(PP)} \quad H_1^p(x_1^p) + H_2^p(x_2^p) + \ldots + H_n^p(x_n^p)$$

When efficient allocation is used at the upper level, the solution x_i^*, $i = 1, \ldots, n$, is obtained from

$$\max_{x_1,\ldots,x_n} H_1(x_1) + H_2(x_2) + \ldots + H_n(x_n)$$

$$\text{s.t.} \quad x_1 + x_2 + \ldots + x_n \le B$$

$$\sum_{j=1}^{m} L_{ij} \le x_i \le \sum_{j=1}^{m} U_{ij}$$

$$x_i \ge 0 \quad i = 1, \ldots, n$$

where $H_i(x_i)$ is determined from the solution to the lower-level problem in population i and is either $H_i^*(x_i)$ or $H_i^p(x_i)$, depending on which method is used at the lower level. Thus, when optimization is used at the upper level, the objective function at the upper level is either

$$\text{(EE)} \quad \max_{x_1,\ldots,x_n} H_1^*(x_1) + H_2^*(x_2) + \ldots + H_n^*(x_n)$$

or

$$\text{(EP)} \quad \max_{x_1,\ldots,x_n} H_1^p(x_1) + H_2^p(x_2) + \ldots + H_n^p(x_n).$$

For (EE), $H_i^*(x_i) = y_{i1}^*(x_i)h_{i1} + \ldots + y_{im}^*(x_i)h_{im}$, where $x_i = \sum_{j=1}^{m} y_{ij}^*(x_i)$. In this case, the lower-level problem becomes irrelevant, and it is as if the upper-level decision maker allocates funds directly to each program in each region.

For (EP), we define p_{ij} as the proportion of funds allocated to region i that would be spent on program j under proportional allocation, according to $y_{ij}^p(x_i) = p_{ij} \times x_i$. Then,

$$H_1^p(x_i) = x_i \sum_{j=1}^{m} p_{ij} h_{ij}$$

if there are no upper limits on the amount of funds allocated to each risk group (and corresponding benefit). If there are funding limits, then the allocation of funds is determined as follows: We sort the population according to U_{ij}/p_{ij} and define $[j]$ so that $U_{i[j]}/p_{i[j]}$ is the j^{th} smallest value of U_{ij}/p_{ij} (i.e., $U_{i[1]}/p_{i[1]}$ is the smallest in region j). Define $U_{i[0]}/p_{i[0]} = 0$ and $U_{i[m+1]}/p_{i[m+1]} = \infty$. Define $b_{i[j]}$ as $b_{i[j]} = \sum_{l=[j]}^{m} p_{i[l]} h_{i[l]}$ and $b_{[m+1]} = 0$. This definition ensures that $b_{i[1]} \geq b_{i[2]} \geq \ldots \geq b_{i[m]}$. Then,

$$H_i^p(x_i) = x_i b_{i[1]}$$

if $x_i \leq U_{i[1]}/p_{i[1]}$ and

$$H_i^p(x_i) = \sum_{j=1}^{k} \left(U_{i[j]}/p_{i[j]} - U_{i[j-1]}/p_{i[j-1]} \right) \times b_{i[j]} +$$

$$\left(x_i - U_{i[k]}/p_{i[k]} \right) \times b_{i[k+1]}$$

if $U_{i[k]}/p_{i[k]} \leq x_i \leq U_{i[k+1]}/p_{i[k+1]}$. This expression for $H_i^p(x_i)$ is nonlinear in x_i. However, we can convert the problem to a linear program by replacing $H_i^p(x_i)$ with $\sum_{j=1}^{m} z_{ij} b_{i[j]}$, setting $x_i = z_{i1} + \ldots + z_{im}$ and adding the constraint $z_{ij} \leq U_{i[j]}/p_{i[j]} - U_{i[j-1]}/p_{i[j-1]}$.

Each variant of the problem that uses optimization can be formulated as a "knapsack" linear program.[19] Such linear programs are easily solved by sorting the objective function coefficients and do not require any special software.

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